AR-001-950

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

ELECTRONICS RESEARCH LABORATORY

TECHNICAL REPORT

ERL-0123-TR

THE SPECTRAL CHARACTERISTICS OF METAL FILM BEAM SPLITTERS

J.R. Venning

S U M M A R Y

The spectral and polarisation characteristics of metallic beam splitters and mirrors made of single films of aluminium, silver, rhodium or nichrome on glass are described. Normal incidence transmission data of each thickness of metal film used in the beam splitter calculations is included for use when measuring or monitoring the deposition of the thin films. The presentation is mostly graphical and intended for the user and maker of simple metal beam splitters.

Approved for Public Release

POSTAL ADDRESS: Chief Superintendent, Electronics Research Laboratory,
Box 2151, G.P.O., Adelaide, South Australia, 5001.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

Users of beam splitters often neglect or are unaware of the spectral characteristics of thin metal films. Polarisation effects of the metal layer can radically change the reflection to transmission ratio of the beam splitter and the resultant polarisation of the reflected and transmitted radiation depends on the polarisation state of the incident beam. The main difficulty in the practical use of beam splitters arises in the specification of the beam splitter required for a particular optical system.

To assist both the user and maker of beam splitters a series of graphs is presented showing the spectral reflection and transmission characteristics of single films of aluminium, silver, rhodium and nichrome as functions of angle of incidence, film thickness, and substrate index. Two basic categories of beam splitters are considered. In the first the metal film is sandwiched between glass and in the second the metal film is between glass and air. Figure 1 is a pictorial summary of the beam splitter configurations considered in this report. The data has been presented so that the effects of locating the beam splitting surfaces in various positions in the optical path can be determined. Opaque metal mirrors and plain glass beam splitters have been included to complete the presentation.

There are many beam splitter designs that use dielectric films by themselves or in conjunction with metal films, but it is not possible to provide detailed information to cover such a wide field. The metal film beam splitter is relatively easy to produce and satisfies the requirements of many optical systems.

The computer programmes used to calculate and draw the characteristics of the beam splitters can be made available if required.

2. DEFINITIONS

It is essential to the correct interpretation of the formulae and diagrams contained in this report that certain terms be defined.

The plane of incidence is the plane that contains the incident and reflected rays. It follows from Snell's law that this plane is normal to the reflecting surface.

Plane polarised radiation is radiation that has the vibrating electric vector confined to one plane. To avoid confusion plane polarised radiation will be described as having its electric vector orientated in a specific direction.

Unpolarised radiation can be considered as a random mixture of all possible orientations of the electric vector.

$\underline{p}$ polarisation refers to the incident radiation polarised with its electric vector parallel to, or contained in, the plane of incidence. This is equivalent to the term "transverse magnetic" or TM wave.

$\underline{s}$ polarisation refers to the incident radiation polarised with its electric vector perpendicular to the plane of incidence. The $\underline{s}$ of $\underline{s}$ polarisation comes from the German senkrecht meaning perpendicular. $\underline{s}$ polarisation is equivalent to "transverse electric" or TE wave.

Polarisers ideally allow only plane polarised radiation to be transmitted (for transmission polarisers) or reflected (for reflection polarisers). The orientation of the electric vector from a polariser can be determined in a simple test. The strongest reflection of specularly reflected sunlight from a horizontal surface is that of light polarised with the electric vector horizontal. Therefore, when viewing such a surface through a transmission polariser the brightest observed reflection is when the polariser is transmitting the horizontal electric vector.

3. CALCULATION OF BEAM SPLITTER CHARACTERISTICS

Two methods of calculation are presented. The matrix formulation given in Section 3.2 is more easily extended to include multilayers than the Fresnel method described in Section 3.1.

3.1 Fresnel coefficient method

The calculation of the reflection and transmission of a single film using Fresnel coefficients is described in most papers introducing thin film theory. (References 1 to 4). The application of these equations to dielectric thin films is straightforward but for thin metal films they require either rearrangement or the manipulation of complex number functions.

The angles of incidence and refraction of the light path are related by Snell's law (see figure 2)

$$n_3 \sin\phi_3 = n_2 \sin\phi_2 \tag{1}$$

$$\text{i.e. } \sin\phi_2 = \frac{n_3}{n_2}\sin\phi_3 \tag{2}$$

and

$$\sin\phi_1 = \frac{n_2}{n_1}\sin\phi_2 \tag{3}$$

$$\cos\phi_2 = \sqrt{1 - \sin^2\phi_2} \tag{4}$$

$$\cos\phi_1 = \sqrt{1 - \sin^2\phi_1} \tag{5}$$

where n_1, n_2, n_3 are the refractive indices of the substrate, film and external medium respectively. ϕ_1, ϕ_2, and ϕ_3 are the refracted and incident angles as shown in figure 2.

The Fresnel reflection and transmission coefficients are

$$r_{2p} = -\frac{n_2\cos\phi_1 - n_1\cos\phi_2}{n_2\cos\phi_1 + n_1\cos\phi_2} \tag{6}$$

$$r_{3p} = -\frac{n_3\cos\phi_2 - n_2\cos\phi_3}{n_3\cos\phi_2 + n_2\cos\phi_3} \tag{7}$$

$$t_{2p} = \frac{2n_2\cos\phi_2}{n_2\cos\phi_1 + n_1\cos\phi_2} \tag{8}$$

$$t_{3p} = \frac{2n_3\cos\phi_3}{n_3\cos\phi_2 + n_2\cos\phi_3} \tag{9}$$

$$r_{2s} = \frac{n_2\cos\phi_2 - n_1\cos\phi_1}{n_2\cos\phi_2 + n_1\cos\phi_1} \tag{10}$$

$$r_{3s} = \frac{n_3\cos\phi_3 - n_2\cos\phi_2}{n_3\cos\phi_3 + n_2\cos\phi_2} \tag{11}$$

$$t_{2_s} = \frac{2n_2 \cos \phi_2}{n_2 \cos \phi_2 + n_1 \cos \phi_1} \tag{12}$$

$$t_{3_s} = \frac{2n_3 \cos \phi_3}{n_3 \cos \phi_3 + n_2 \cos \phi_2} \tag{13}$$

where the suffixes on r and t refer to the interface and the polarisation for which the coefficient is applicable.

Summing the amplitudes for multiple reflections and omitting the polarisation subscripts the amplitude reflection and transmission coefficients for the single film are given by;

$$R = \frac{r_3 + r_2 \exp(-2i\delta_2)}{1 + r_2 r_3 \exp(-2i\delta_2)} \tag{14}$$

$$T = \frac{t_2 t_3 \exp(-i\delta_2)}{1 + r_2 r_3 \exp(-2i\delta_2)} \tag{15}$$

where

$$\delta_2 = \frac{2\pi}{\lambda} n_2 d_2 \cos \phi_2 \tag{16}$$

$$d_2 = \text{physical thickness of film}$$

and δ_2 is called the phase thickness of the film.

The relative energies crossing a unit area per second normal to the incident, reflected, and transmitted beams are given by

$$\mathbf{R} = R R^* \tag{17}$$

for the reflected beam and

$$\mathbf{T}a = \frac{n_1}{n_3} T T^* \tag{18}$$

for the transmitted beam where R* and T* are the complex conjugates of R and T. $\mathbf{T}a$ is the intensity transmission coefficient.

The transmission characteristic can also be defined in terms of the ratio of the total flux transmitted to that incident on a unit area of the film;

$$\text{i.e.} \quad \mathbf{T}_b = \frac{n_1}{n_3} \frac{\cos \phi_1}{\cos \phi_3} T T^* \tag{19}$$

where the cosine terms take into account changes in beam cross section. $\mathbf{T}_b$ is the energy transmission coefficient. The absorption is given by

$$A = 1 - \mathbf{R} - \mathbf{T}_b \tag{20}$$

$$\text{i.e.} \quad \mathbf{R} + \mathbf{T}_b = 1$$

for a non absorbing film.

In the case of an absorbing film the refractive index n_2 is complex and hence the phase thickness δ_2 and angle ϕ_2 are complex. The complex value of n_2 can be substituted wherever n_2 appears and provided the rules of complex arithmetic are followed the equations (17), (18) and (19) are valid.

3.2 Matrix method

The matrix method of formulation (references 1 to 5) is a convenient alternative to the substitution method of Section 3.1. While applicable to the case of a single film between medium and substrate its main attraction is the ease with which it can be adapted for use with multiple films. This description will outline the solution of the single film problem.

The incident, reflected and refracted beams of radiation are calculated in terms of the tangential components of their electric and magnetic field vectors. The tangential components of the incident beam are a function of the polarisation of the incident radiation and angle of incidence. For radiation incident at angle ϕ and with the electric vector in the plane of incidence (p polarisation).

$$E_{(\text{Tangential})} = E \cos \phi$$

$$H_{(\text{Tangential})} = H$$

The effective refractive index U

$$U = \frac{H_{(\text{Tangential})}}{E_{(\text{Tangential})}} = \frac{H}{E \cos \phi} = \frac{n}{\cos \phi}$$

where n, the refractive index, is equal to H/E by definition. For radiation incident at angle ϕ and the electric vector perpendicular to the plane of incidence (s polarisation).

$$E_{(\text{Tangential})} = E$$

$$H_{(\text{Tangential})} = H \cos \phi$$

and

$$U = \frac{H \cos \phi}{E} = n \cos \phi$$

The total tangential components of electric and magnetic field strength are continuous at an interface; this condition leads to the following relationships (following Weinstein).

$$E(J+1) = E(J) \cos g(J) + \frac{i}{U(J)} H(J) \sin g(J) \qquad (24)$$

$$H(J+1) = iU(J)\, E(J) \sin g(J) + H(J) \cos g(J) \qquad (25)$$

where

$$g(J) = \frac{2\pi}{\lambda} n(J)\ d(J)\ \cos \phi(J)$$

$$d(J) = \text{physical thickness of Jth layer}$$

$$U(J) = n(J)/\cos \phi(J) \text{ for p polarisation} \tag{26}$$

or

$$U(J) = n(J) \cos \phi(J) \text{ for s polarisation} \tag{27}$$

dependent on whether the incident light is polarised with the electric vector in (p polarisation), or perpendicular to (s polarisation), the plane of incidence.

E(J) and H(J) are the total tangential components of the electric and magnetic field strength at the interface of layers J and J-1; see figure 2. Similarly E(J+1) and H(J+1) relate to the interface between layers J+1 and J. The quantity g(J) is the effective optical thickness (phase thickness) of layer J and is equivalent to δ of equation 16. The quantity U(J) may be taken as a generalised effective refractive index of layer J and its value depends on the angle of incidence and the polarisation.

Expressing the above equations in matrix form gives

$$\begin{bmatrix} E(J+1) \\ H(J+1) \end{bmatrix} = \begin{bmatrix} \cos g(J) & \frac{i}{U(J)} \sin g(J) \\ iU(J) \sin g(J) & \cos g(J) \end{bmatrix} \begin{bmatrix} E(J) \\ H(J) \end{bmatrix} \tag{28}$$

i.e. for the single layer

$$\begin{bmatrix} E(3) \\ H(3) \end{bmatrix} = \begin{bmatrix} \cos g(2) & \frac{i}{U(2)} \sin g(2) \\ iU(2) \sin g(2) & \cos g(2) \end{bmatrix} \begin{bmatrix} E(2) \\ H(2) \end{bmatrix} \tag{29}$$

The initial conditions are given by

$$E(2) = E^{+}(1) = 1 \tag{30}$$

and

$$H(2) = U(1)\ E^{+}(1) = U(1).1 \tag{31}$$

where $E^{+}(1)$ is the tangential component of the electric field strength in layer (1) travelling in the forward direction. The tangential component of the incident beam is described as $E^{+}(J + 1)$ and the reflected beam as $E^{-}(J + 1)$ where the superscript indicates the direction and the subscript the layer number.

Evaluation of the matrix for the single layer problem is trivial giving equations 24 and 25.

i.e.
$$E(3) = E(2) \cos g(2) + \frac{i}{U(2)} H(2) \sin g(2)$$

$$H(3) = iU(2)\, E(2) \sin g(2) + H(2) \cos g(2)$$

From the total tangential components of the electric and magnetic field strength vectors the solution for the tangential components of the directed vectors are

$$E^{+}(3) = 0.5\left(E(3) + \frac{H(3)}{U(3)} \right)$$

$$E^{-}(3) = 0.5\left(E(3) - \frac{H(3)}{U(3)} \right)$$

The equations relating the tangential components of the electric vector to amplitude reflection and transmission coefficients are

$$\left.\begin{aligned} R &= \frac{E^{-}(3)}{E^{+}(3)} \\ T &= \frac{E^{+}(1)}{E^{+}(3)} \cdot \frac{\cos \phi(3)}{\cos \phi(1)} \end{aligned}\right\} \text{p polarisation}$$

$$\left.\begin{aligned} R &= \frac{E^{-}(3)}{E^{+}(3)} \\ T &= \frac{E^{+}(1)}{E^{+}(3)} \end{aligned}\right\} \text{s polarisation}$$

The energy reflection and transmission coefficients are

$$\mathbf{R} = RR^{*}$$

and

$$\mathbf{T}_b = \frac{n(1) \cos \phi(1)}{n(3) \cos \phi(3)} TT^{*}$$

where $\mathbf{T}_b$ is the transmission coefficient considering total flux incident and transmitted through a unit area of thin film.

For non absorbing films $\mathbf{R} + \mathbf{T}_b = 1$.

For absorbing films n(2) is complex and hence $\phi(2)$ and g(2) are complex.

3.3 Beam splitters

Beam splitter configurations are numerous and it is not practicable to provide data for all possible designs. There are two broad divisions; the first is where the beam splitting surface is sandwiched between glass and the second where the beam splitting surface is deposited on glass and is in contact with air. Some basic types of beam splitters are illustrated in figure 1.

Calculations have been performed at different angles of incidence in order that enough data is available for a realistic appreciation of the problems associated with making and specifying beam splitters. The calculations are restricted to single metal films and two different substrates.

To assist in the manufacture of the beam splitters, normal incidence transmission data of thin metal films of relevant thickness on glass have also been calculated. Because of the large amount of data involved only a representative sample of the data is included and discussed in this report. The full series of graphical data, available from this laboratory, provides detailed information for the user and maker of thin metal film beam splitters.

A word of explanation about some of the figures is probably required at this stage. Most of the figures have been plotted on a computer driven graphics device and because of the limited character set readily available there are no lower case characters in the legend. The thickness of each film has been specified in terms of optical thickness at a specified wavelength, e.g. "ND = 0.01 at 550 NM" means that the optical thickness of the film, the product of refractive index and physical thickness,

$$nd = 0.01\lambda = 0.01(550) = 5.5 \text{ nm}.$$

3.3.1 Type 1

The type 1 beam splitter is illustrated in figure 1 and calculated data for this arrangement is presented graphically in figures 3 to 6. The metallic film is deposited on one prism and the assembly cemented together. This physical arrangement effectively stabilises the metal film. It is tacitly assumed that the cement has the same refractive index as the substrate material and therefore does not enter into the calculation.

The computation is arranged so that the relative energies reflected and transmitted by the film are calculated in a medium of glass. It is then a simple matter to allow separately for the effect of any other interface in the optical path.

3.3.2 Type 2

The type 2 beam splitter is illustrated in figure 1 and calculated data for this arrangement is presented graphically in figure 7. The computation is arranged so that the reflected beam is in a glass medium and the transmitted beam is in air.

The transmission calculation in this arrangement, as in the other arrangements, is in terms of energy transmitted through a unit area of film.

3.3.3 Type 3

The type 3 beam splitter is illustrated in figure 1 and calculated data for this arrangement is presented graphically in figure 8. The computation is arranged so that the reflected beam is in air and the transmitted beam is in glass. The transmission data is calculated in terms of total energy transmitted.

3.3.4 Type 4

The type 4 beam splitter is illustrated in figure 1 and calculated data for this arrangement is presented graphically in figure 9. The effects of multiple reflection within the substrate have been included. Physically a plate beam splitter spreads both the reflected and transmitted beams because of multiple reflections within the substrate.

The calculation of relative energy reflected and transmitted requires some care in the choice of transmission coefficient used. It is probably safer to use energy coefficients for each part of the system although a mixture of coefficients may be used.

The transmission of the beam splitter is given by

$$T_T = T1I.TFI(1 + BR1.RF + (BR1.RF)^2 \ldots.)$$

$$= \frac{T1I.TFI}{(1 - R1.RF)}$$

and the reflection given by

$$R_T = R1 + T1E.BT1E.RF(1 + RF.BR1 + (RF.BR1)^2 \ldots.)$$

$$= R1 + \frac{T1E.BT1E.RF}{1 - RF.BR1}$$

$$= R1 + \frac{T1E^2.RF}{1 - RF.R1}$$

where (figure 28)

T1I = intensity transmission coefficient of interface 1

TFI = intensity transmission coefficient of film system

T1E = energy transmission coefficient of interface 1

BT1E = energy transmission coefficient of interface 1 in the reverse direction

R1 = reflection coefficient of interface 1

BR1 = reflection coefficient of interface 1 in the reverse direction

RF = reflection coefficient of film system

T1E = BT1E

R1 = BR1

The transmission and reflection coefficients T_T and R_T refer to the total energy transmitted or reflected from the plate beam splitter.

It should be noted that the intensity transmission coefficient of an air/glass interface is not equal to the transmission coefficient of a glass/air interface for oblique incidence. This is brought about by the change in beam cross section due to refraction across the interface. However the energy transmission coefficients are the same for each direction.

It is assumed that no interference effects occur in the substrate.

3.3.5 Type 5

The type 5 beam splitter is illustrated in figure 1 and calculated data for this arrangement is presented graphically in figure 10. The effects of multiple reflections within the substrate have been included.

The transmission of the beam splitter is given by

$$T_T = \frac{TFI.T3I}{1 - R3.BRF}$$

and the reflection by

$$R_T = RF + \frac{TFI.BTFI.R3}{1 - R3.BRF}$$

where (figure 29)

TFI = intensity transmission coefficient of film system

BTFI = intensity transmission coefficient of film system in the reverse direction

T3I = intensity transmission coefficient of interface 3

RF = reflection coefficient of film system

BRF = reflection coefficient of film system in reverse direction

R3 = reflection coefficient of interface 3

TFI $\neq$ BTFI

RF $\neq$ BRF

The transmission and reflection coefficients T_T and R_T refer to the total energy transmitted or reflected from the plate beam splitter. It is assumed that no interference effects occur in the substrate.

3.3.6 Type 6

The type 6 calculation is for an opaque film of material. The reflectance of the mirror has been calculated with materials of refractive index 1.9, 1.5 and 1.0 (air) in contact with the top surface of the film; figures 11 to 18 show the reflectance of the metal mirrors in mediums of refractive index 1.0 and 1.5.

The Fresnel amplitude coefficients are given by

$$r_p = -\frac{n_2 \cos \phi_1 - n_1 \cos \phi_2}{n_2 \cos \phi_1 + n_1 \cos \phi_2}$$

and

$$r_s = \frac{n_2 \cos \phi_2 - n_1 \cos \phi_1}{n_2 \cos \phi_2 + n_1 \cos \phi_1}$$

where n_2 and ϕ_2 refer to the medium and n_1 and ϕ_1 refer to the mirror material.

The intensity reflection coefficient

$$\mathbf{R} = r.r^*$$

for each polarisation direction.

3.3.7 Type 7

For completeness the characteristics of plain air/glass and glass/air interfaces are included together with the glass plate beam splitter. The calculations are for total energy transmitted and reflected including the effects of multiple reflections; see figures 1, 19 and 20.

The intensity or energy reflection coefficient for a single air/glass interface

$$R = r^2$$

where

$$r_p = -\frac{n_2 \cos \phi_1 - n_1 \cos \phi_2}{n_2 \cos \phi_1 + n_1 \cos \phi_2}$$

and

$$r_s = \frac{n_2 \cos \phi_2 - n_1 \cos \phi_1}{n_2 \cos \phi_2 + n_1 \cos \phi_1}$$

for the required polarisation and angle of incidence.

Assuming that there is no absorption in the substrate the total reflection from the plate

$$R_T = \frac{2R}{1 + R} \quad ,$$

the total transmission

$$T_T = \frac{1 - R}{1 + R}$$

and

$$R_T + T_T = 1$$

for each polarisation.
Each internal reflection in the plate has the effect of spreading the transmitted and reflected beams for oblique incidence.

3.3.8 Deposition monitors

A common method of determining the thickness of material deposited on a surface is to measure the change in transmission through a glass monitor piece in the vapour stream during deposition. The spectral

transmission at normal incidence of thin films of metal on a glass substrate are provided as information for the monitoring process. All thicknesses of material used in the type 1 to 5 beam splitters are considered in the type 8 calculation. The effects of multiple reflections within the substrate (type 4 of figure 1 at normal incidence) are included in the calculations of the transmission data presented in figures 21-24.

4. DISCUSSION OF RESULTS

The effects of polarisation in metal film beam splitters cannot be ignored. The effects are generally predictable although there are unexpected results in some situations.

4.1 Beam splitter performance related to polarisation

The following example illustrates a commonly occurring problem associated with the use and specification of beam splitters.

A specification calls for cubic beam splitters to be used at a spectral wavelength of 500 nm and the ratio of the reflected to transmitted beams is to be 1:1. Assuming that the incident beam is unpolarised and polarisation in the output beams can be tolerated then, by reference to figure 3, it can be seen that an aluminium film with an optical thickness of 0.01λ at 550 nm would be satisfactory. The reflected and transmitted beams each contain about 40% of the incident energy and hence there is about 20% loss in the beam splitter. While the incident beam is considered unpolarised the reflected beam, containing 40% of the energy, is polarised with about 25% of the energy polarised in the s direction and 15% in the p direction. Similarly the transmitted beam is polarised with 15% in the s direction and 25% in the p direction. Provided no other oblique incidence reflections occur and the detection system is insensitive to polarisation then the beam splitter satisfies the specification.

If the incident beam is plane polarised with the electric vector in the plane of incidence (p polarisation) then the above beam splitter is no longer a 1:1 beam splitter but is a 3:5 beam splitter. For s polarised light it would be a 5:3 beam splitter. Hence the same beam splitter could behave quite differently when used in a different location or orientation in an optical system.

This example merely illustrates the presence of a problem and was not chosen to show a spectacular variation. By using figure 3 again and an optical thickness of aluminium of 0.02λ at 550 nm then a nominal 4:1 beam splitter at 750 nm could vary from 9:1 down to 2.8:1 depending on the polarisation of the input beam or polarising effects introduced between the beam splitter and the detector.

4.2 Variation of polarisation with angle of incidence

The reflection and transmission coefficients of the metal film beam splitters are a function of the angle of incidence and film thickness as well as the medium and substrate materials. Figure 25 shows the reflection and transmission coefficients of a type 1 aluminium beam splitter as a function of incidence angle and film thickness. These parameters have been determined at a constant wavelength of 600 nm and the results are representative of the effects to be expected at other wavelengths. Figure 25 shows that as the thickness of the film changes the differences in the coefficients for the two polarisations also change. Comparison of figure 25 and figure 11 at a wavelength of 600 nm shows that the effects of polarisation in reflection first increase as the film thickness increases and then after reaching a maximum value decline until the film becomes opaque; e.g. at an angle of

incidence of 45 degrees the differences between the reflection coefficients for each polarisation are 0.18, 0.25, 0.19 and 0.07 for thicknesses 0.005, 0.01, 0.02 ND at 550 nm, as shown in figure 25, and the opaque film of figure 11 respectively.

Figure 27, showing the variation of the reflection and transmission characteristics of a type 3 aluminium beam splitter as a function of angle of incidence and film thickness, is similar to figure 25. The film thicknesses are slightly less than for figure 25 but it is apparent that the type 3 configuration, while showing similar trends, is different from the type 1 situation.

Figure 26 shows the characteristics of a type 1 silver beam splitter and the variation with angle of incidence and film thickness. The behaviour is similar to that of the aluminium films. However from figure 4 it will be noted that at shorter wavelengths ($<$ 380 for the case considered) the reflection and transmission coefficients for s and p polarisations are inverted; i.e. $R_p > R_s$ and $T_s > T_p$. At 380 nm, the crossover point, $R_s = R_p$ and $T_s = T_p$ at all angles of incidence. The index of the substrate influences the wavelength location of this crossover point. For a substrate index of 1.9 the crossover point is at 400 nm.

A similar effect was looked for in a type 1 gold beam splitter near 550 nm; i.e. the middle of the absorption edge. While there was a crossover in the transmission coefficients at 550 nm there was no crossover in the reflection coefficients.

The behaviour of rhodium and nichrome with regard to change of characteristics with angle of incidence and thickness is similar to that of aluminium.

4.3 Type 2 beam splitter

The type 2 beam splitter is a special case because for an angle of incidence beyond the critical angle of the substrate there is no transmission into the outside medium. This can be demonstrated using equations 1 to 5

$$n_3 \sin \phi_3 = n_2 \sin \phi_2 = n_1 \sin \phi_1$$

$$\text{i.e.} \quad \sin \phi_1 = (n_3 \sin \phi_3)/n_1$$

When

$$n_3 \sin \phi_3 > n_1$$

then

$$\sin \phi_1 > 1$$

and

$$\cos \phi_1 = \sqrt{1 - \sin^2 \phi_1} \text{ becomes imaginary.}$$

$$\text{i.e.} \quad \cos \phi_1 = -i\sqrt{|1 - \sin^2 \phi_1|}$$

Under these conditions there may be a non zero solution for the real component of the calculated intensity transmission coefficient but there is a zero solution for the real component of the energy transmission coefficient.

Vasicek(ref.11) shows that the imaginary component of cos ϕ_1 must be -ve for the evanescent wave in medium 1 to decay exponentially with distance. The reflection coefficients change rapidly near the critical angle and graphs of the reflection coefficients for thin aluminium films are presented in figure 30 as a function of angle of incidence.

4.4 Mirrors

Figures 11 to 18 show the spectral reflectance of opaque metal mirrors for different angles of incidence. Comparison of these curves with the beam splitter curves show that the polarisation effects in the reflection coefficients are generally not as great for the mirrors as they are for the beam splitters. The other difference to note in the comparison is that the shape of the mirror curves are different from the shape of the semi transparent films. This illustrates the fact that because the reflectance curves of the mirror surfaces are spectrally flat it does not necessarily follow that the reflectance of the semi transparent film is spectrally flat.

The refractive index of the medium in which reflection occurs does affect the reflection coefficients. The material least affected is silver as can be seen from comparison of the relevant curves of figures 11 to 18.

4.5 General comments

The beam splitter characteristics of types 1, 2, 3 and 6 are intended as building blocks in the calculation of the spectral and polarisation characteristics of a complete optical system. The results of the type 4, 5, 6 and 7 calculations can be used as separately identifiable elements. The spectral characteristics of the four materials have been limited to the visible and near visible region for this report as this is a region of common interest.

The computations and subsequent graphical presentation in other spectral regions are only limited by the knowledge of the optical constants of the materials involved. Single film beam splitters for the infrared would possibly use different materials depending on the spectral wavelength of interest.

The choice of materials for this report was made on the basis of common local useage, with the exception of rhodium. Rhodium was included because of its corrosion resistance and acceptance by the Royal Navy. Therefore it was considered a potentially useful material for Australian projects.

The criteria for the selection of materials for single film beam splitters and mirrors include spectral shape, polarisation effects, stability, absorption and depending on the environment, corrosion resistance and physical hardness.

NOTATION

A	total energy absorption coefficient
BR1	reflection coefficient of interface 1 in the reverse direction
BRF	reflection coefficient of film system in the reverse direction
BT1E	energy transmission coefficient of interface 1 in the reverse direction
BTFI	intensity transmission coefficient of film system in the reverse direction
E	electric vector
H	magnetic vector
R	total amplitude reflection coefficient for interference system
$\mathbf{R}$	total intensity reflection coefficient
R_T	total reflection coefficient of parallel plate beam splitter
R1	reflection coefficient of interface 1
R3	reflection coefficient of interface 3
RF	reflection coefficient of film system
T	total amplitude transmission coefficient for interference system
$\mathbf{T}_a$	intensity transmission coefficient
$\mathbf{T}_b$	energy transmission coefficient
T_T	total transmission coefficient of parallel plate beam splitter
T1E	energy transmission coefficient of interface 1
T1I	intensity transmission coefficient of interface 1
T3I	intensity transmission coefficient of interface 3
TFI	intensity transmission coefficient of film system
U	effective refractive index
d	thickness of film
g	phase thickness of film
i	$\sqrt{-1}$
k	absorption coefficient
n	refractive index
p	electric vector parallel to plane of incidence

r	amplitude reflection coefficient
s	electric vector perpendicular to plane of incidence
t	amplitude transmission coefficient
δ	phase thickness of film
ϕ	angle of incidence or refraction
λ	wavelength

REFERENCES

No.	Author	Title
1	Heavens, O.S.	"Optical Properties of Thin Solid Films". (London, Butterworths Scientific Publications, 1955)
2	Berning, P.H.	"Theory and Calculations of Optical Thin Films". Physics of Thin Films, Vol.1 (New York, Academic Press, 1963)
3	Heavens, O.S.	"Optical Properties of Thin Films". Progress in Physics, Vol.23 (London, The Physical Society, 1960)
4	Weinstein, W.	"Computations in Thin Film Optics". Vacuum, Vol.IV, No.1, January 1954
5	Brown, M.S.	"The Computed Performance of Thin Film Filters at Oblique Incidence". WRE-TN-571(AP), February 1972
6	Hass, G.	"Mirror Coatings". Applied Optics and Optical Engineering, Vol.III (New York, Academic Press, 1966)
7	Drummeter, L.F. and Hass, G.	"Solar Asorptance and Thermal Emittance of Evaporated Coatings". Physics of Thin Films, Vol.II (New York, Academic Press, 1964)
8	Crosby, P.	"Optical Constants of Metals and Alloys". MSc Thesis, University of London, 1952
9	Bolotin, G.A. and Chukina, T.P.	"Optical Constants of Rhodium". Optical Spectra. USSR, Vol.23, p.333, 1967
10	Venning, J.R.	"Measurement of the Optical Properties of Gold Nichrome and Germanium by Ellipsometry". WRE-TN-1373, April 1975
11	Vasicek, A.	"Optics of Thin Films". (Amsterdam, North Holland Publishing Company, 1960)

APPENDIX I

OPTICAL CONSTANTS DATA

The optical constants data used for aluminium(ref.6-7), silver(ref.6-8), rhodium(ref.9), and nichrome(ref.10) are tabulated in Tables 1 to 4.

Table I.1

Optical Constants of Aluminium

λ (nm)	n	k
300	0.25	3.33
350	0.325	3.82
400	0.40	4.40
450	0.51	5.00
500	0.66	5.60
550	0.83	6.00
600	1.08	6.60
650	1.30	7.11
700	1.55	7.00
750	1.80	7.12
800	1.99	7.05
850	2.08	7.15
900	1.96	7.70
950	1.75	8.50

Table I.2

Optical Constants of Silver

λ(nm)	n	k
300	1.4	0.8
320	0.90	0.3
340	0.20	1.0
360	0.12	1.3
400	0.10	1.9
500	0.10	2.85
600	0.10	3.7
700	0.13	4.25
800	0.18	4.9
900	0.20	5.75
1000	0.24	6.5

Table I.3

Optical Constants of Rhodium

λ(nm)	n	k
400	0.84	3.91
500	1.09	4.17
600	1.43	4.62
700	1.68	5.67
800	2.03	6.36
900	2.27	6.50
1000	2.33	6.8

Table I.4

Optical Constants of Nichrome

λ(nm)	n	k
350	1.53	2.416
361	1.64	2.51
400	1.72	2.65
450	1.90	2.89
500	2.08	3.07
550	2.25	3.28
600	2.43	3.44
650	2.62	3.64
700	2.81	3.79

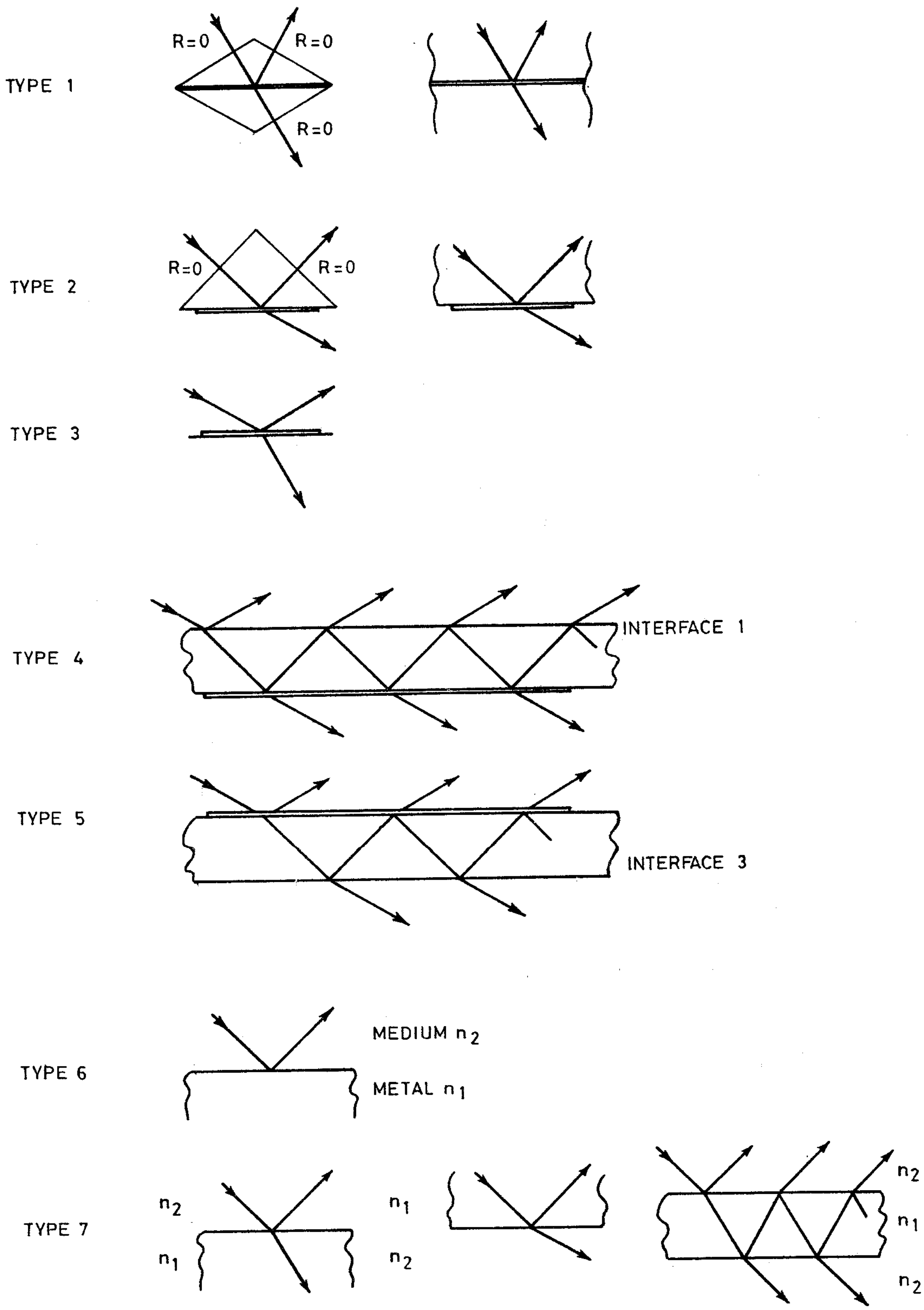


Figure 1. Beam splitters

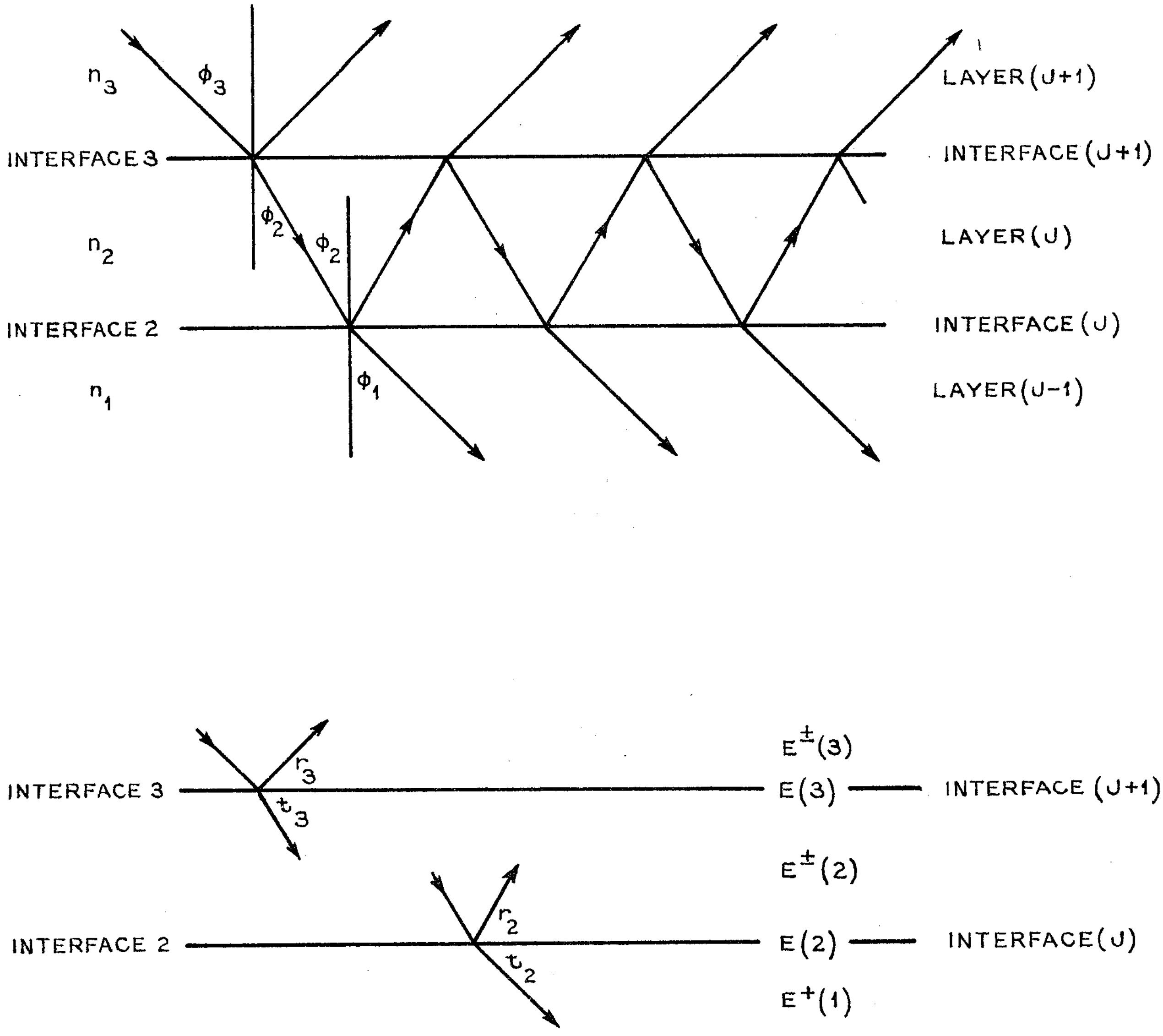


Figure 2. Thin film bounded by two media

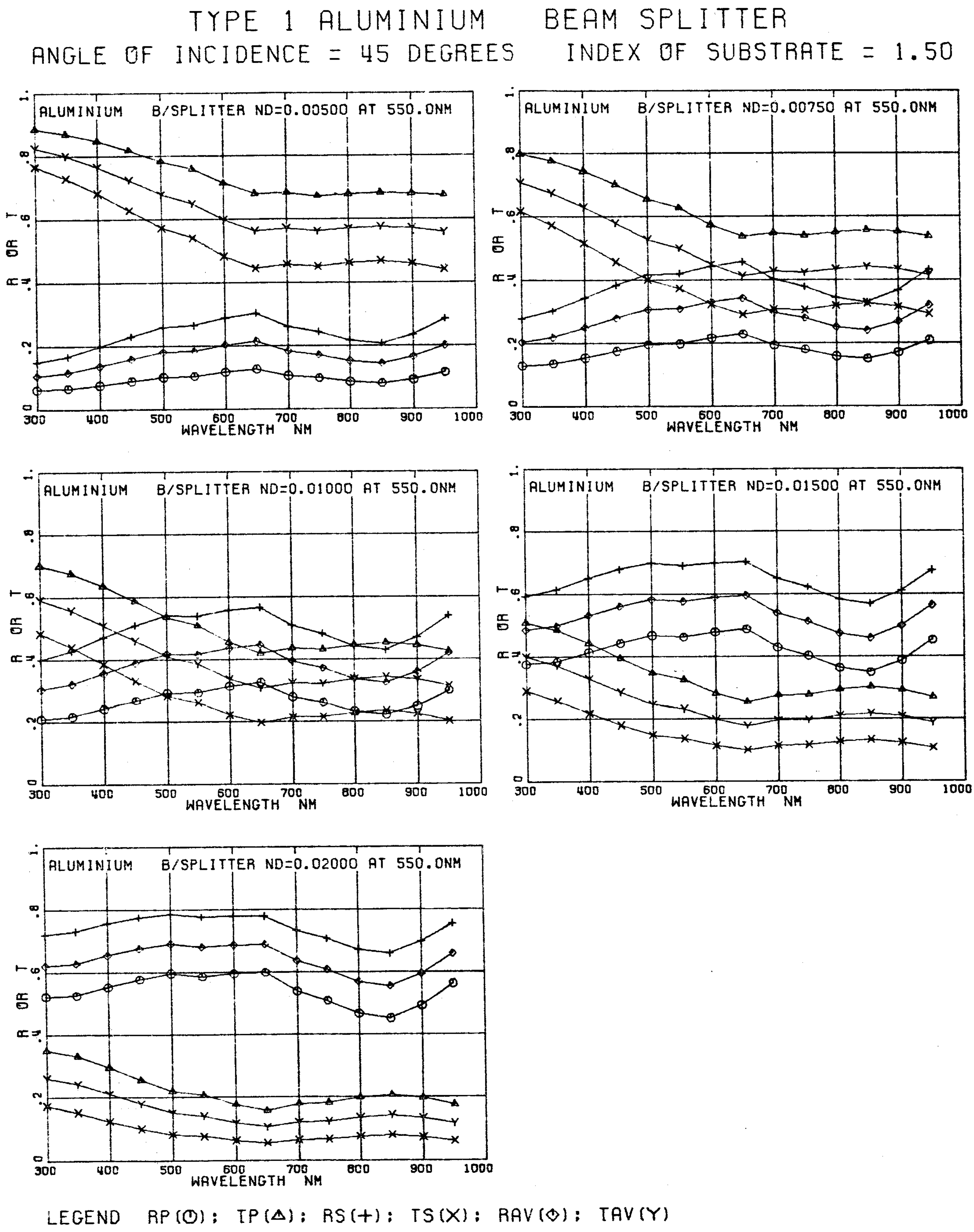


Figure 3. Type 1 Aluminium beam splitter

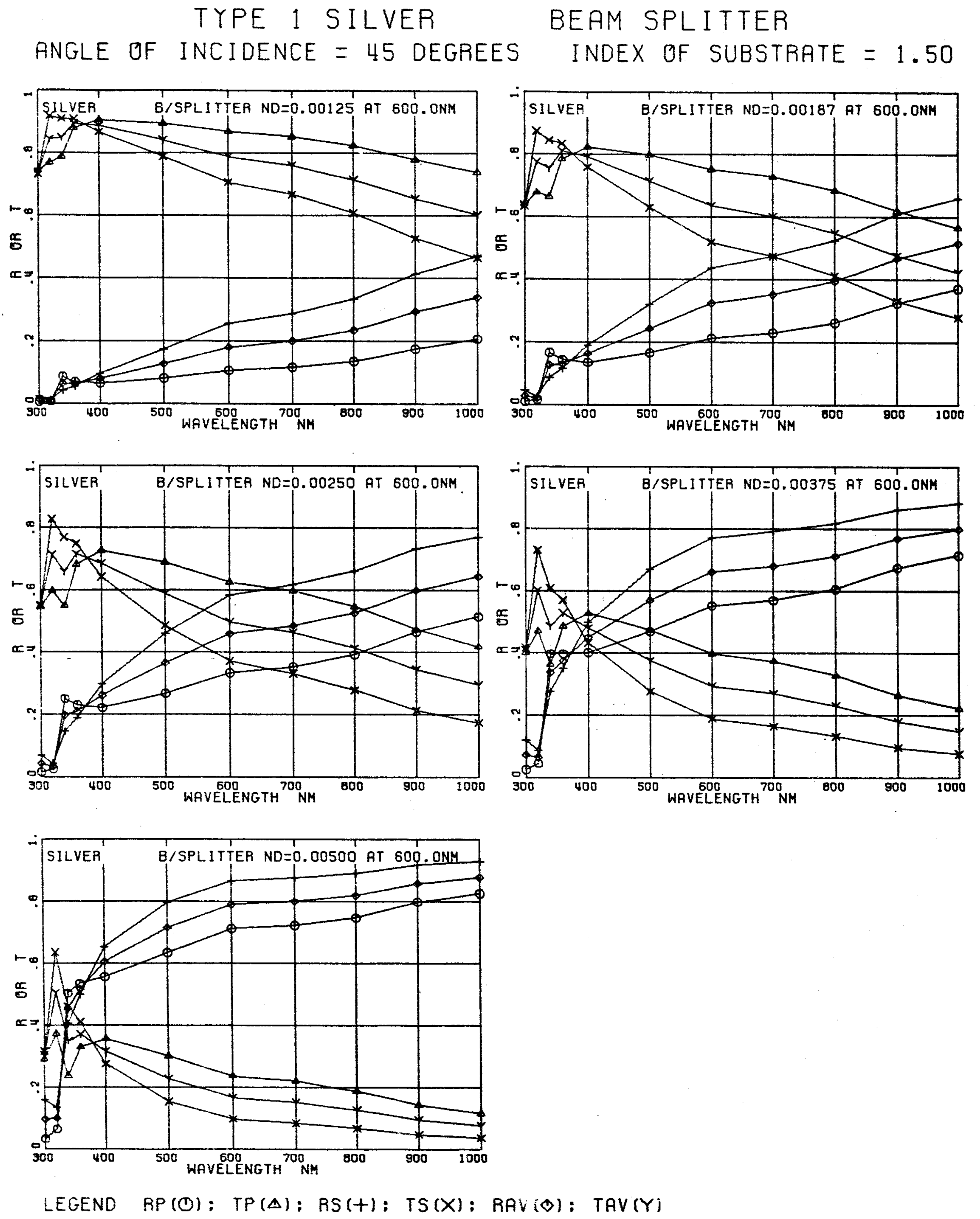


Figure 4. Type 1 Silver beam splitter

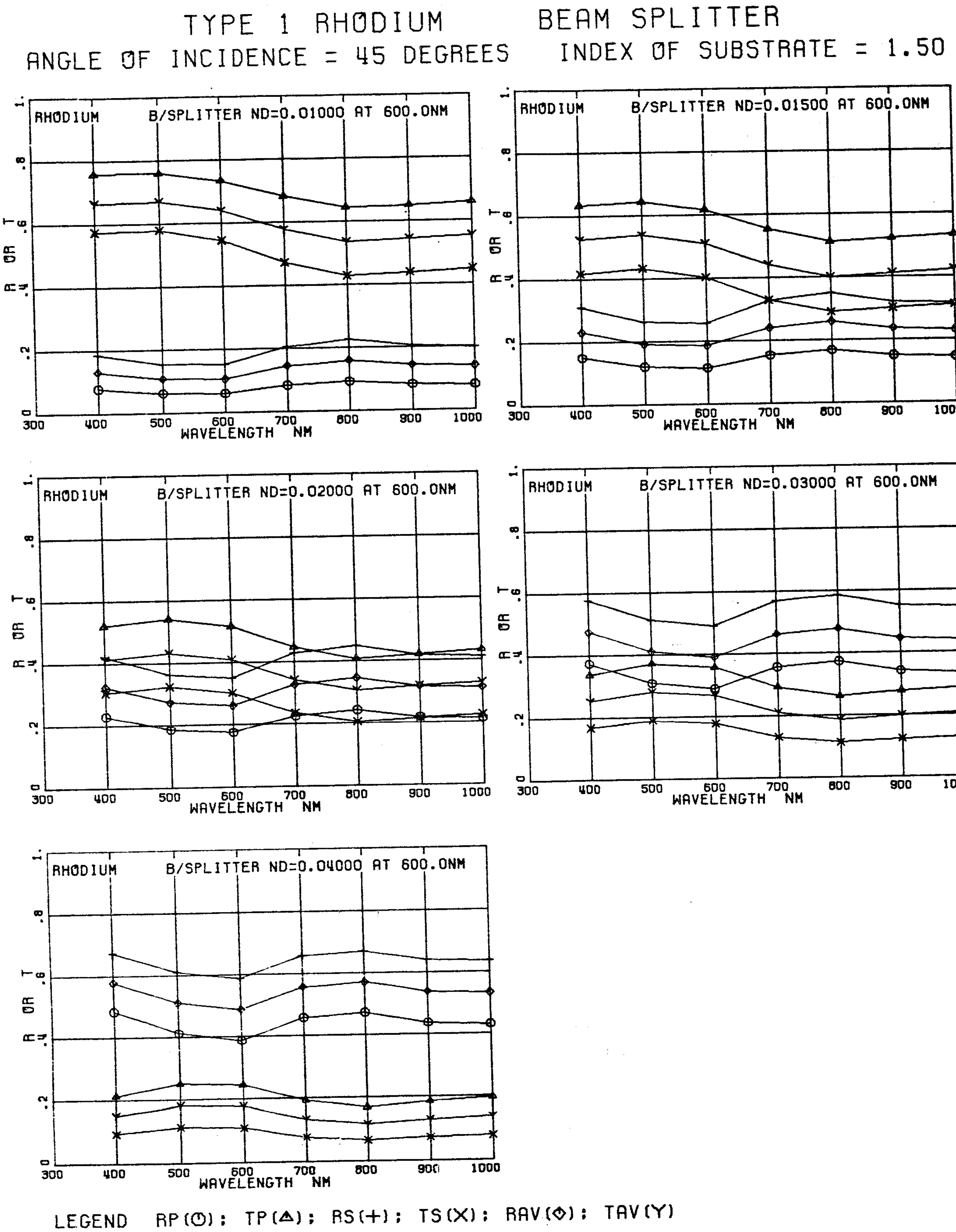


Figure 5. Type 1 Rhodium beam splitter

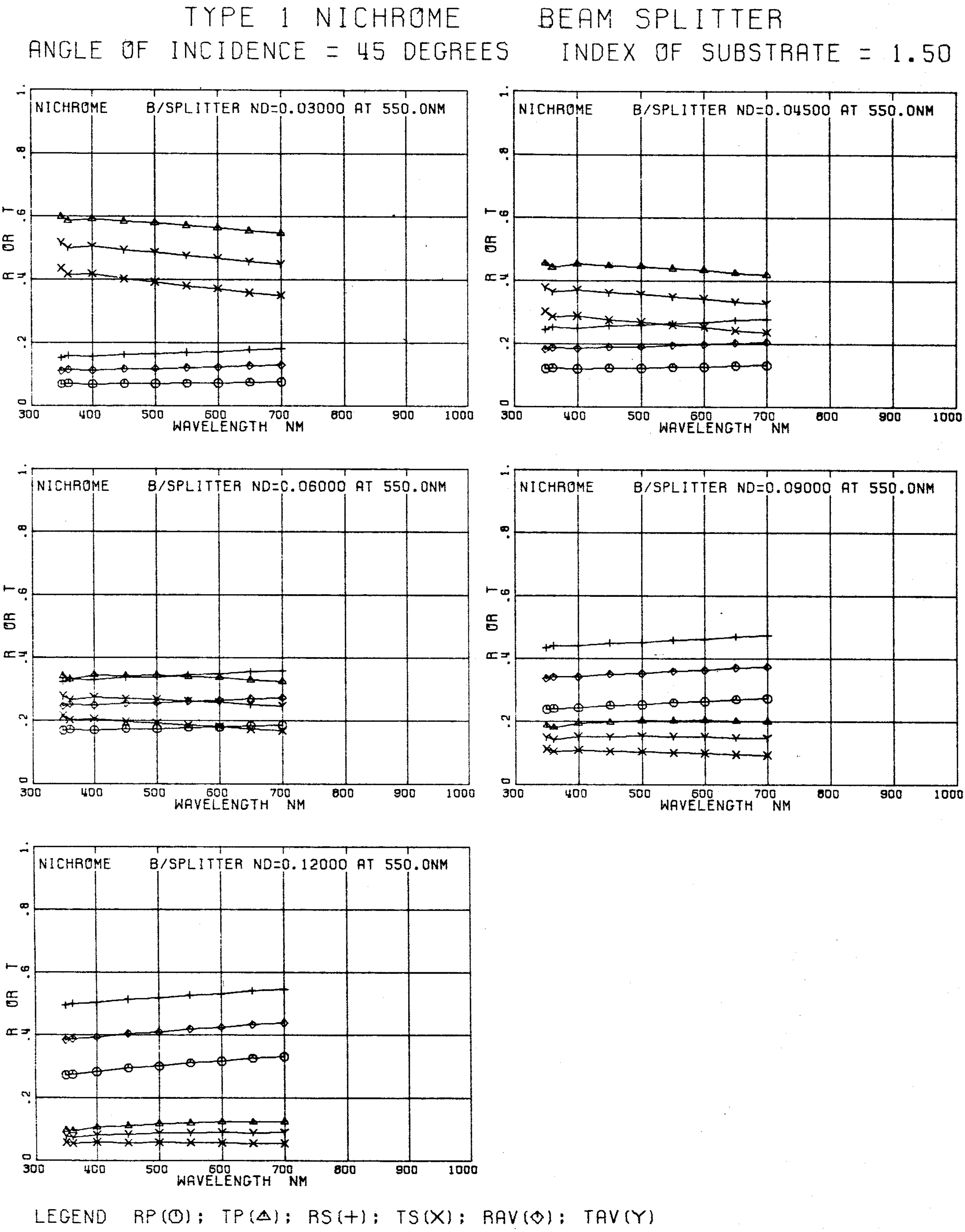


Figure 6. Type 1 Nichrome beam splitter

Type 2 Beam splitter

Angle of incidence = 45 degrees Index of substrate = 1.50

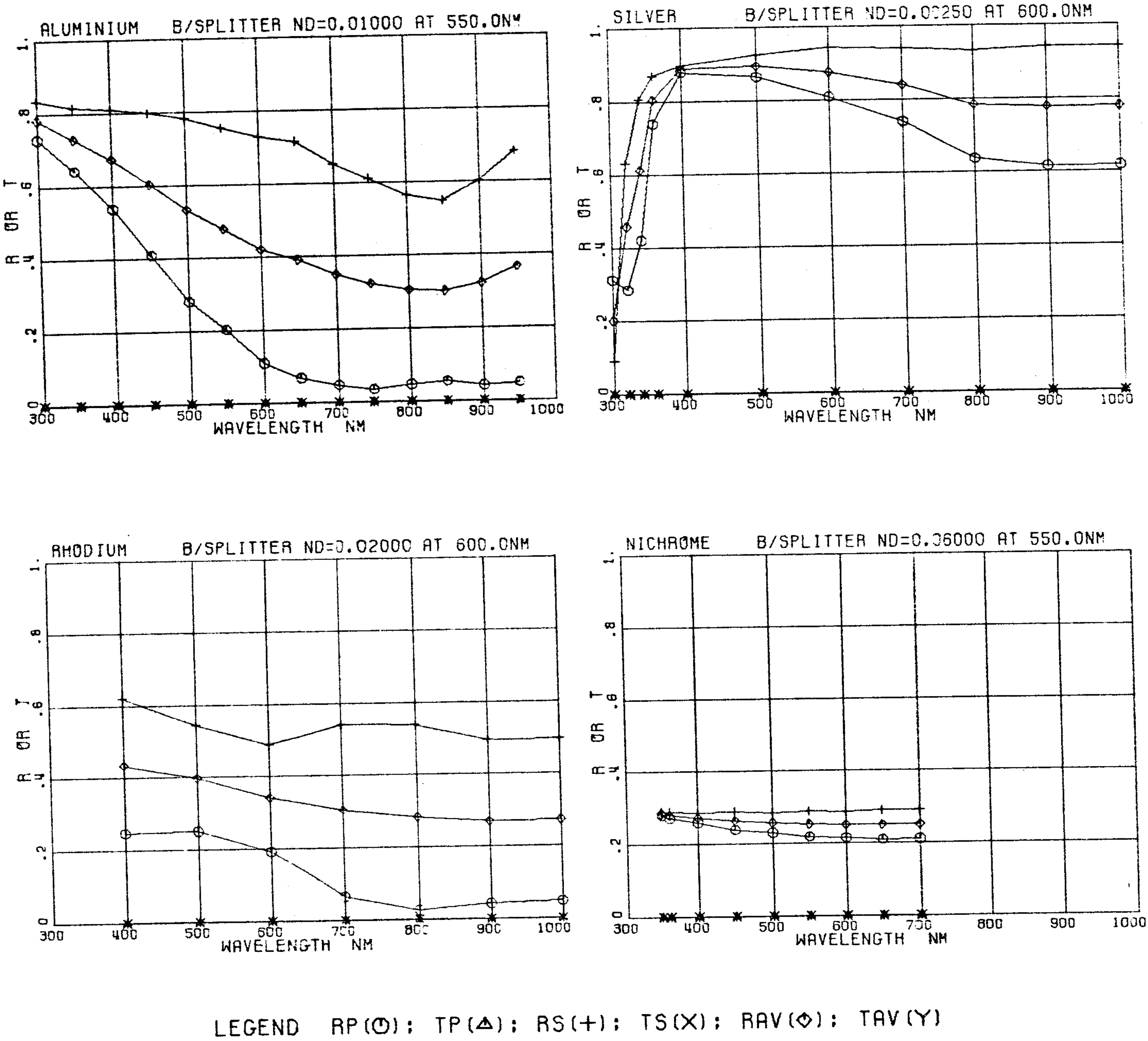
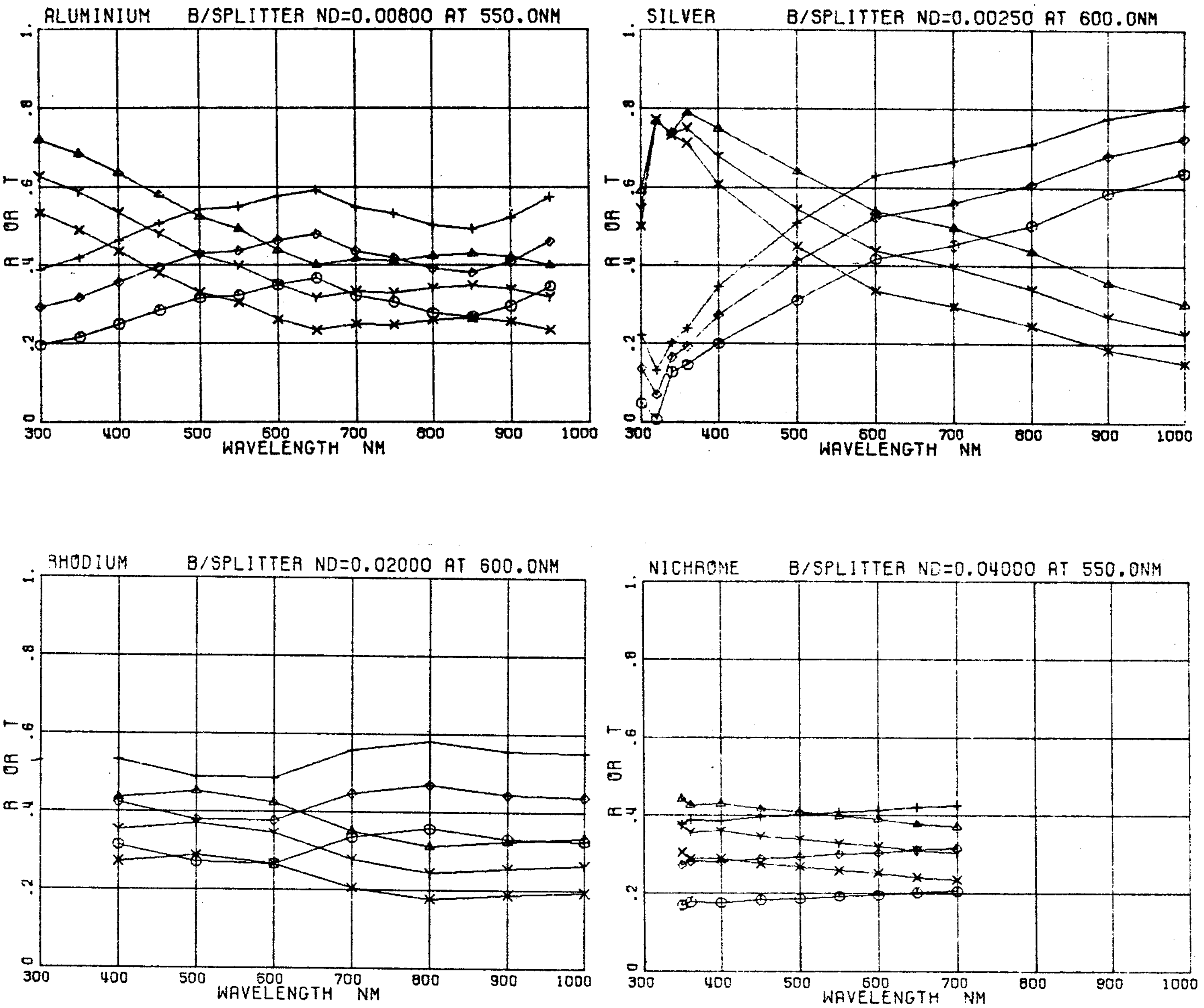


Figure 7. Type 2 beam splitter

Type 3 Beam splitter

Angle of incidence = 45 degrees Index of substrate = 1.50



LEGEND RP(O); TP(Δ); RS(+); TS(X); RAV(◇); TAV(Y)

Figure 8. Type 3 beam splitter

Type 4 Beam splitter

Angle of incidence = 45 degrees   Index of substrate = 1.50

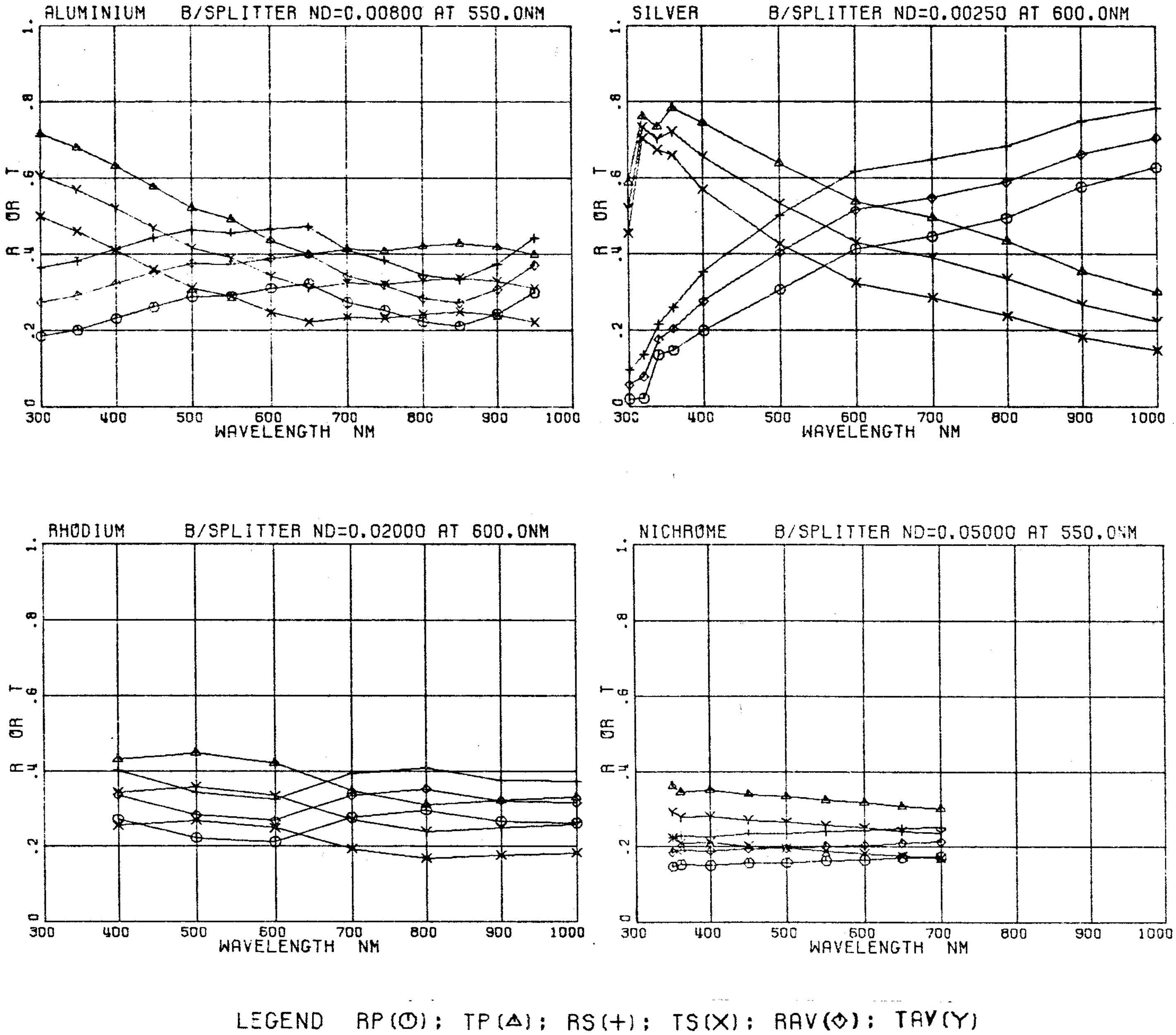


Figure 9. Type 4 beam splitter

Type 5 Beam splitters

Angle of incidence = 45 degrees   Index of substrate = 1.50

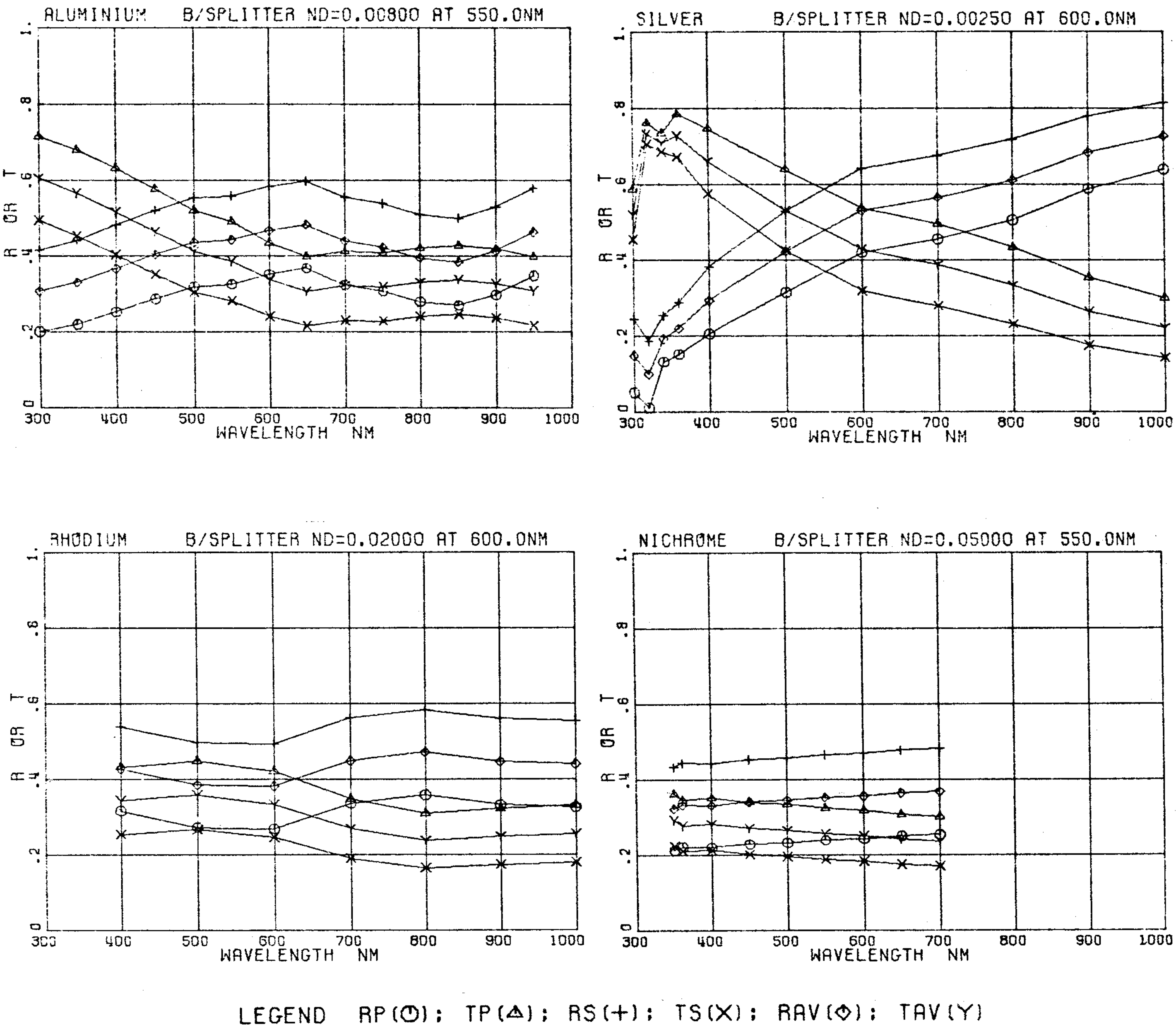


Figure 10. Type 5 beam splitter

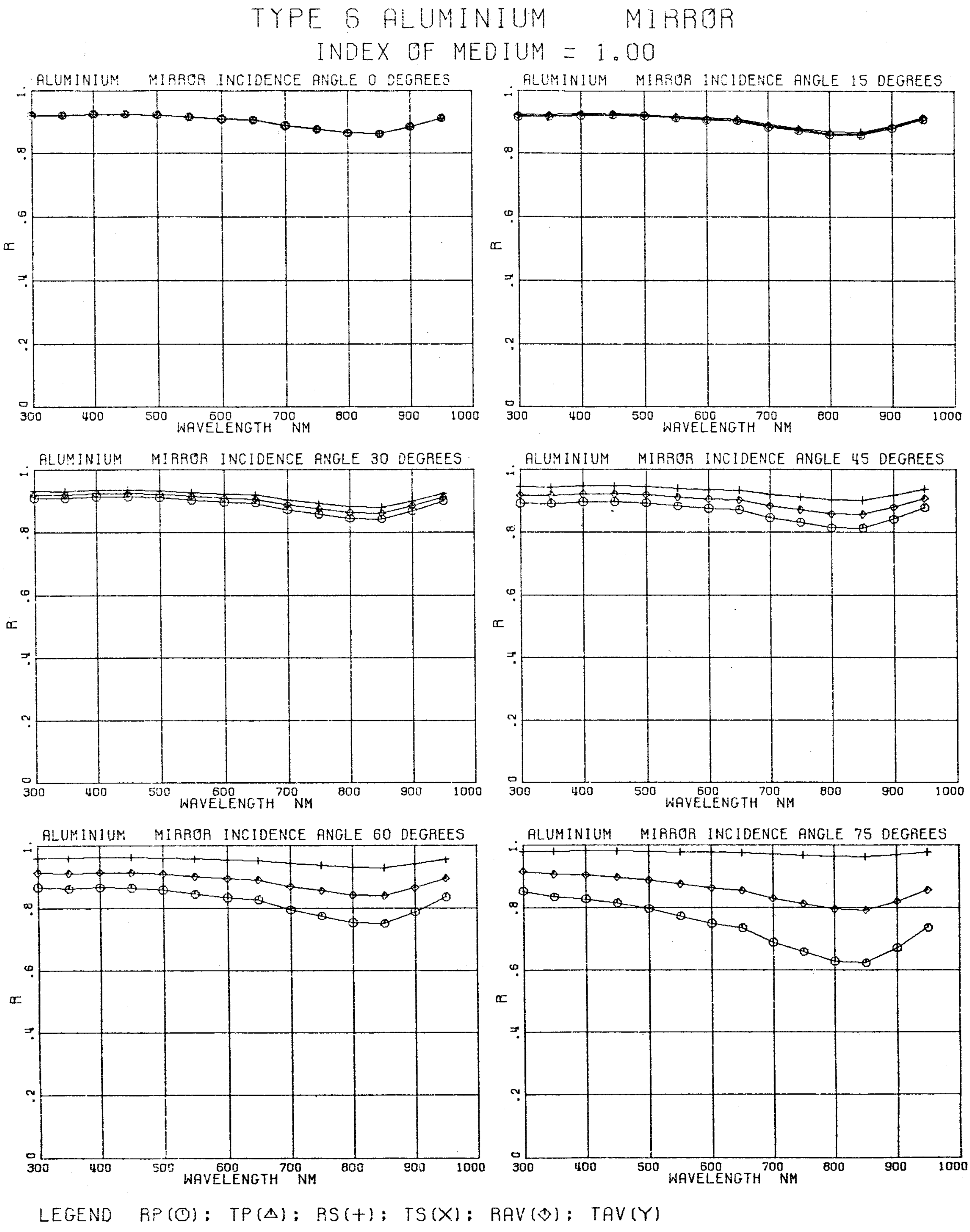


Figure 11. Aluminium mirror

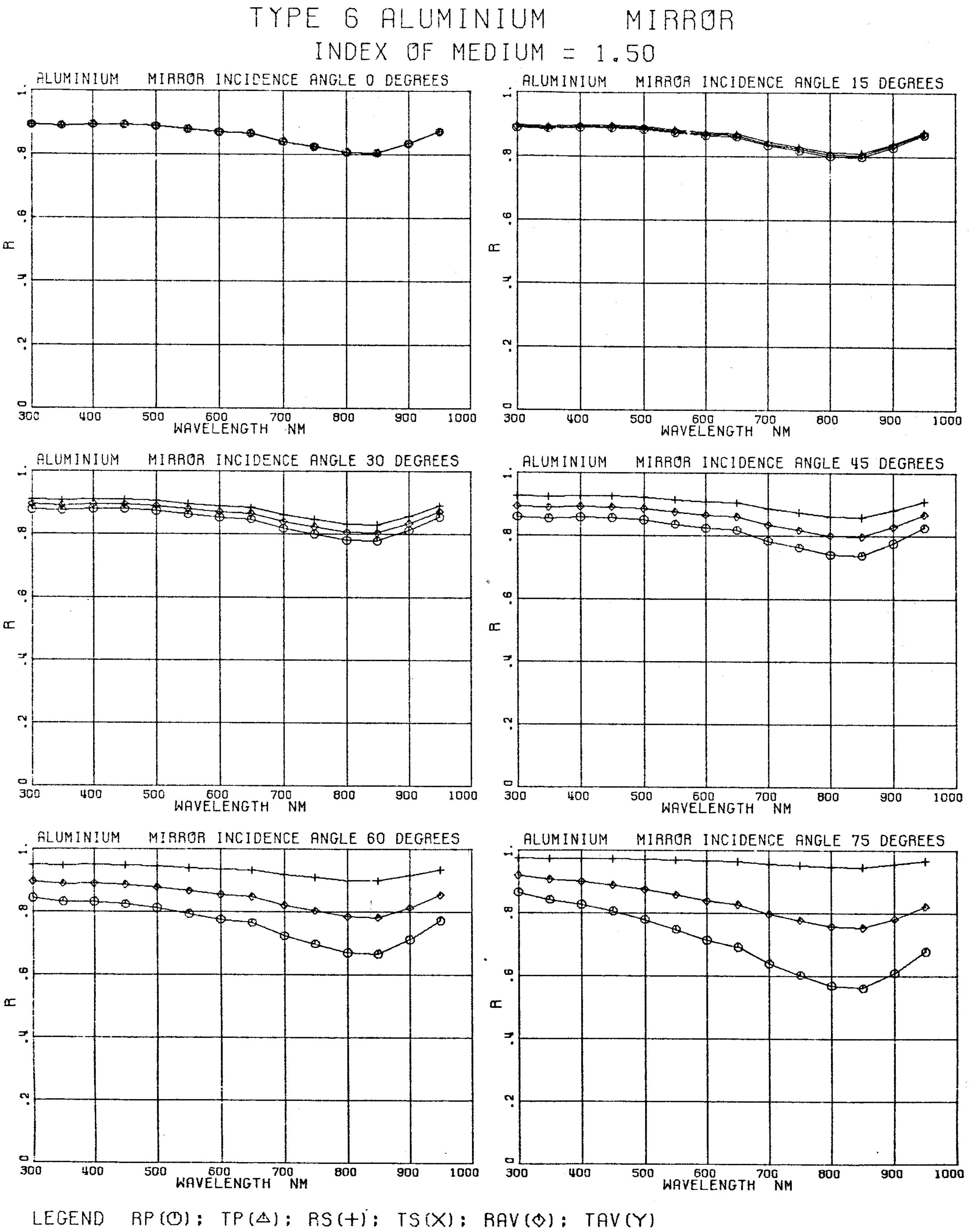


Figure 12. Aluminium mirror

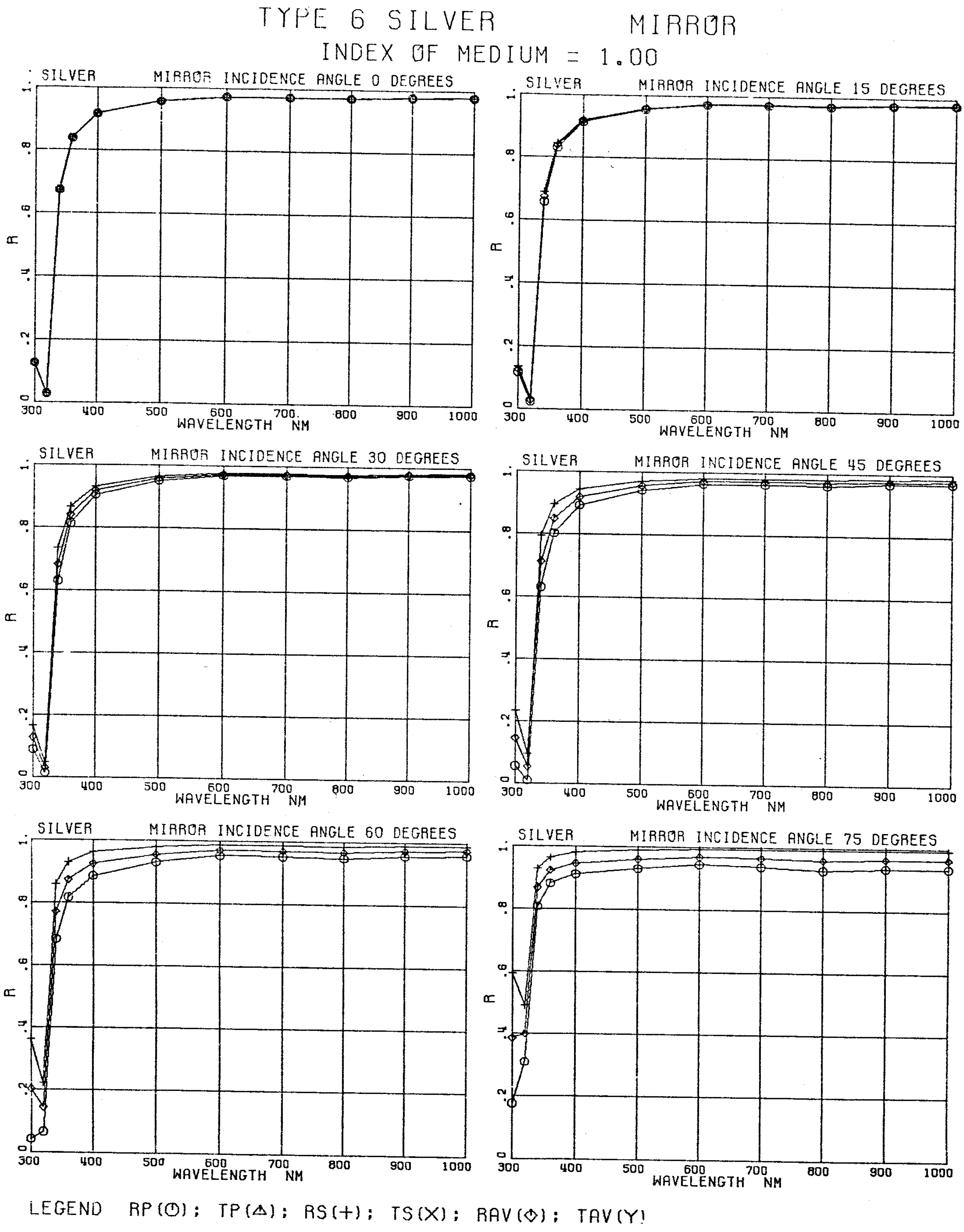


Figure 13. Silver mirror

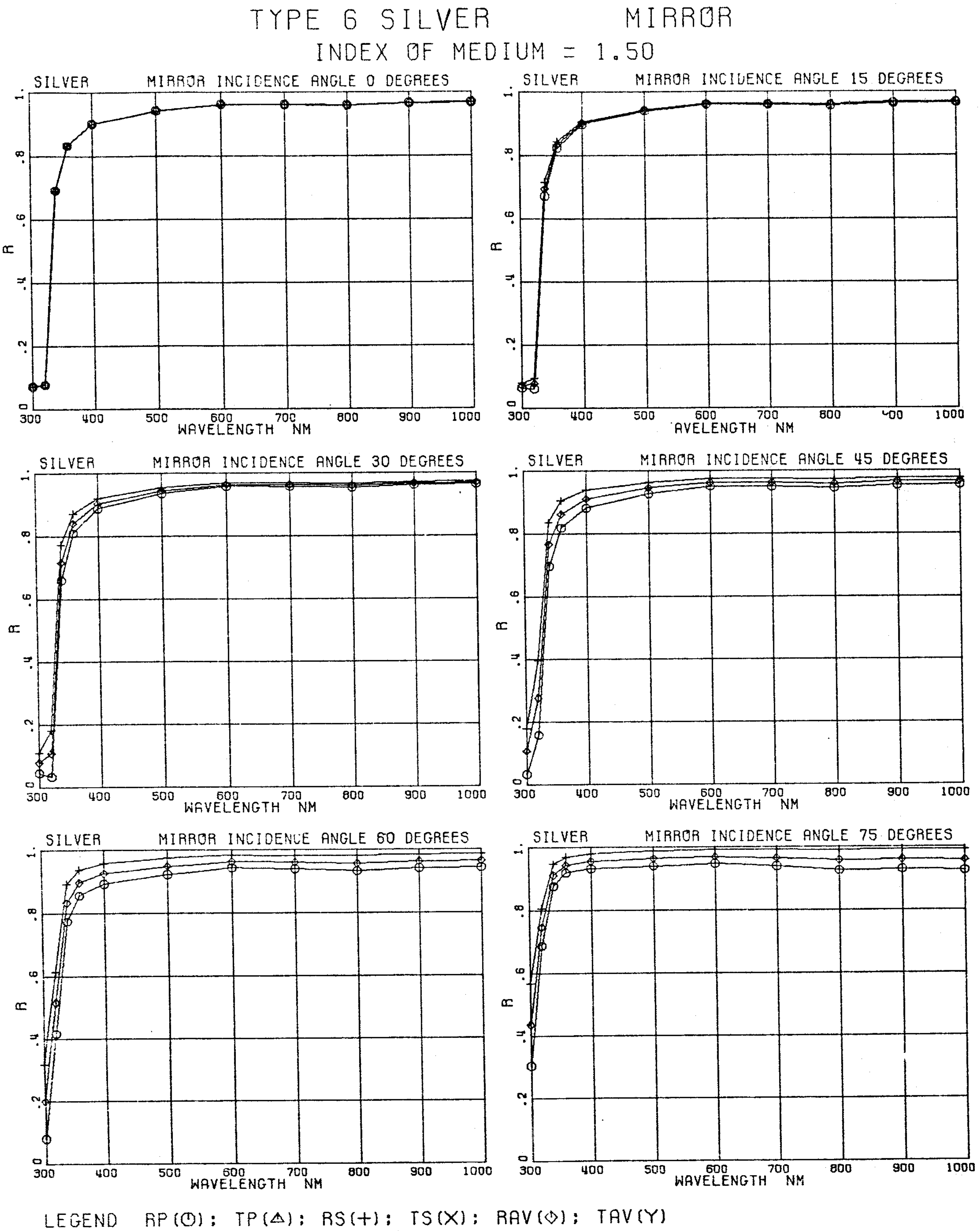


Figure 14. Silver mirror

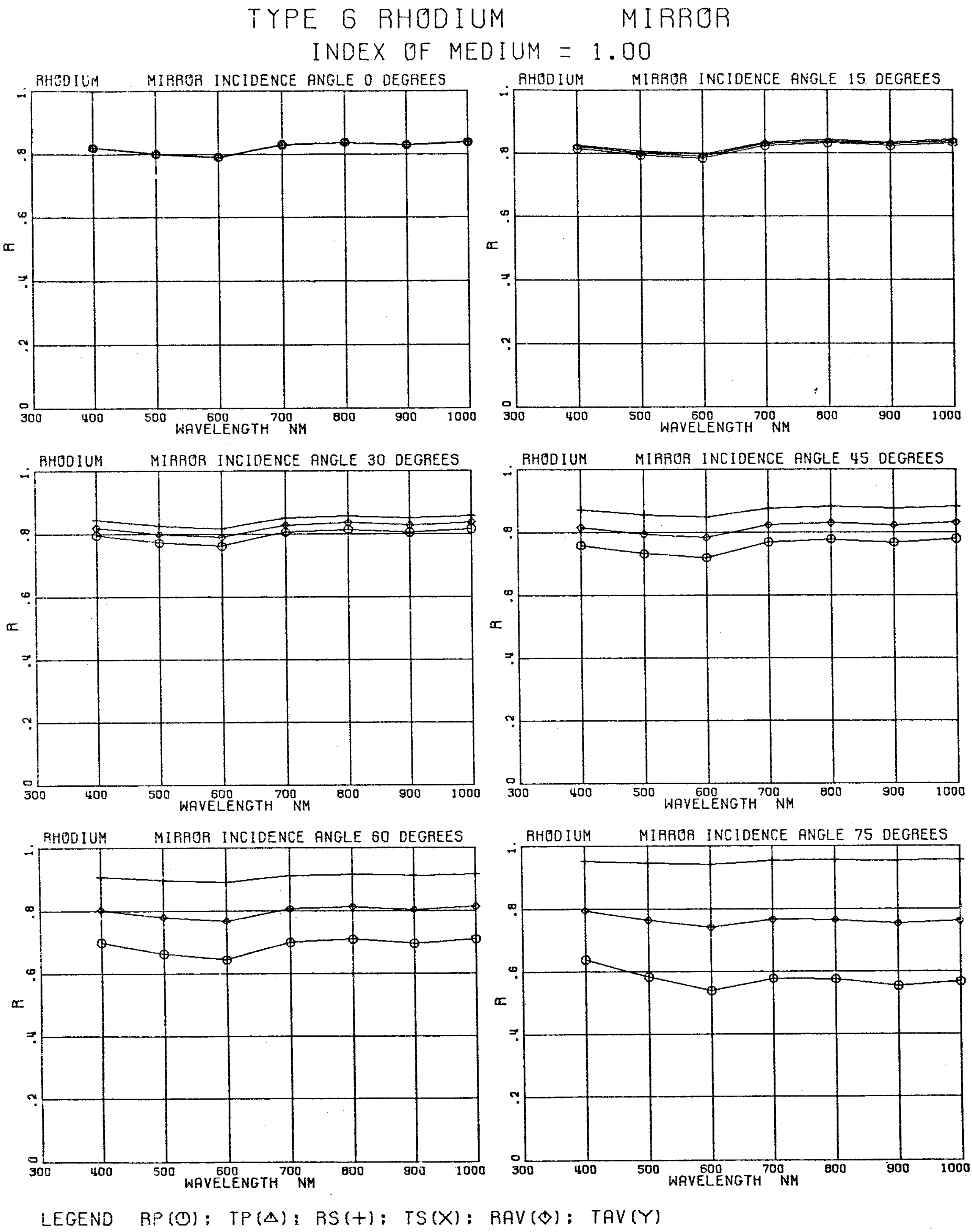


Figure 15. Rhodium mirror

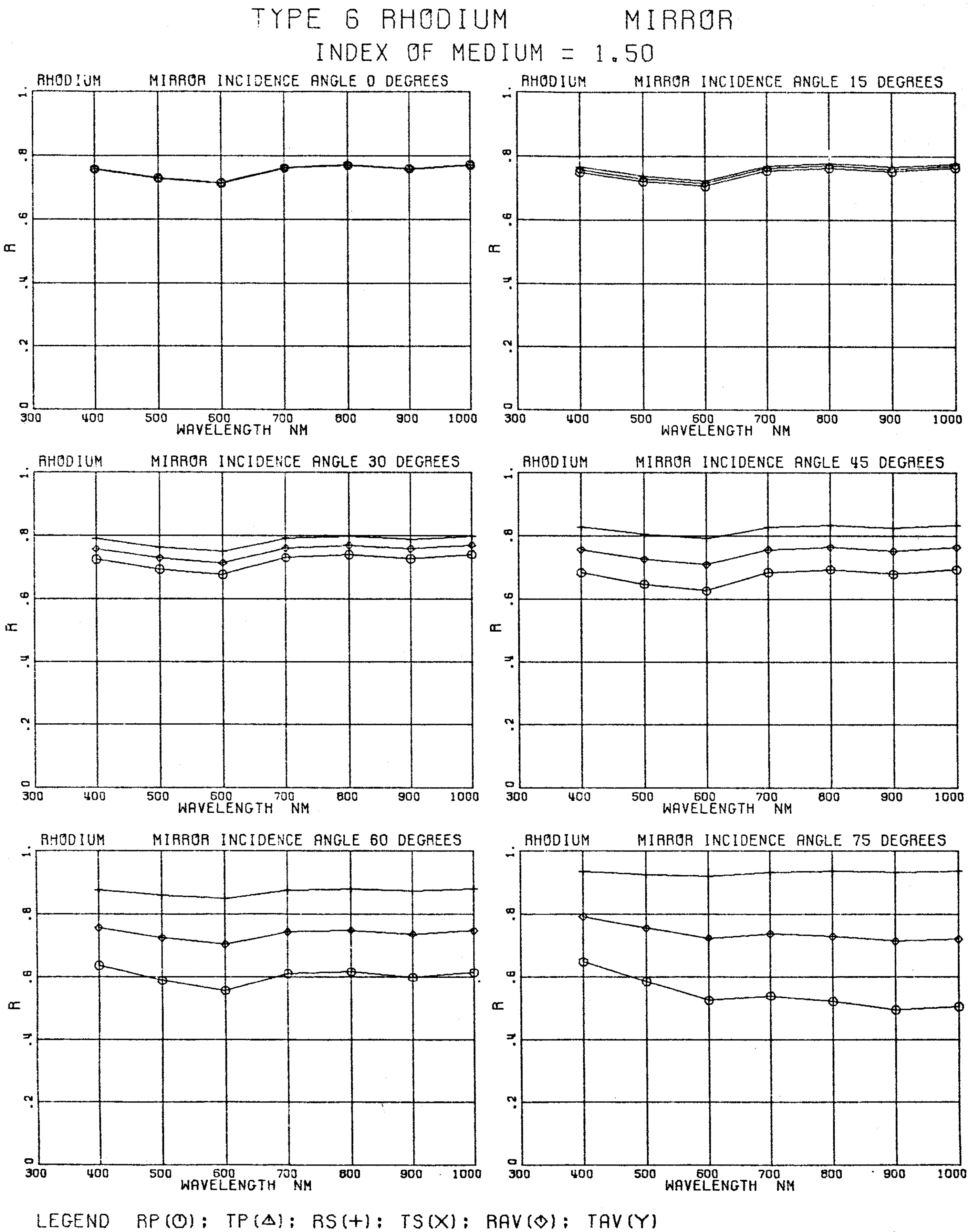


Figure 16. Rhodium mirror

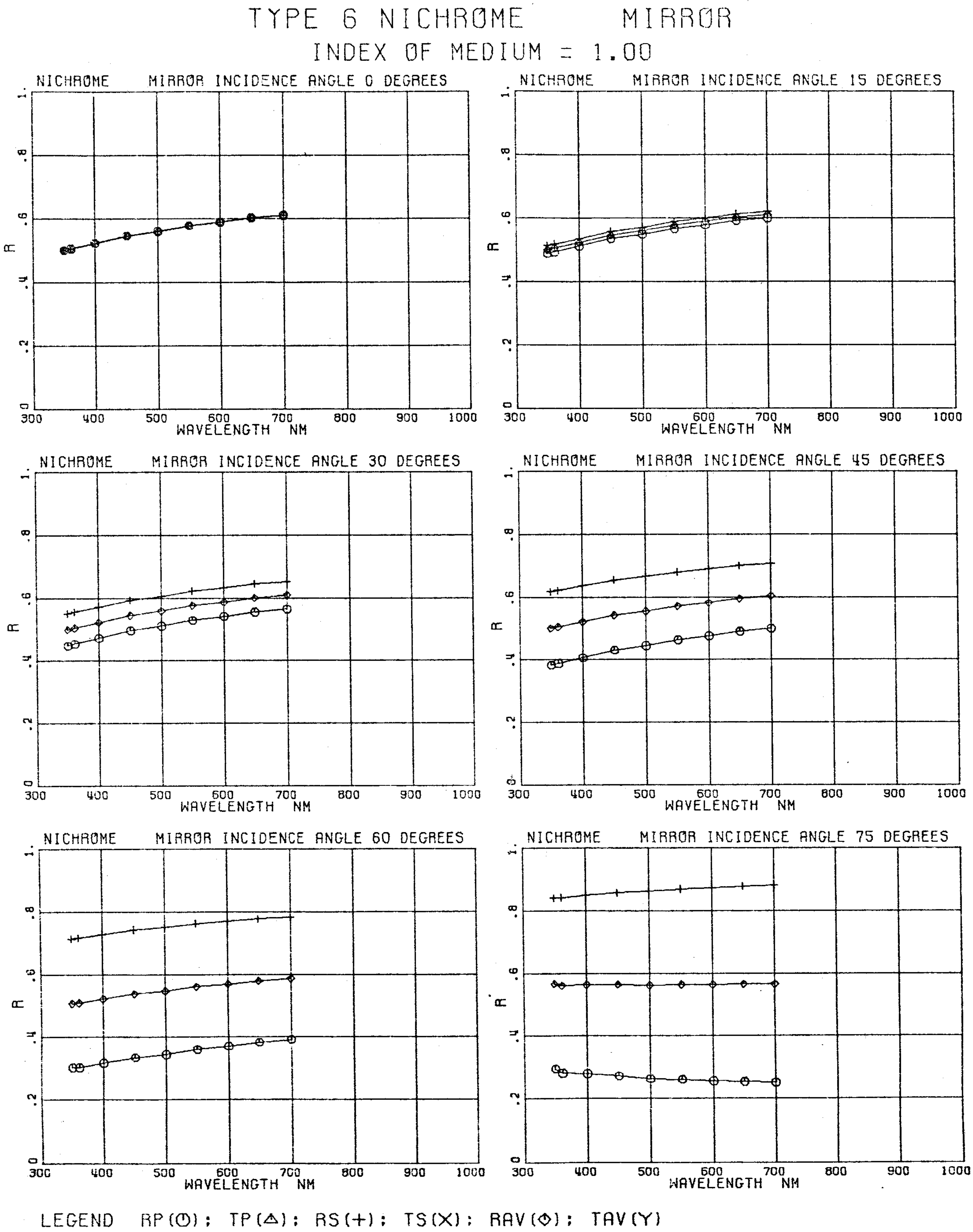


Figure 17. Nichrome mirror

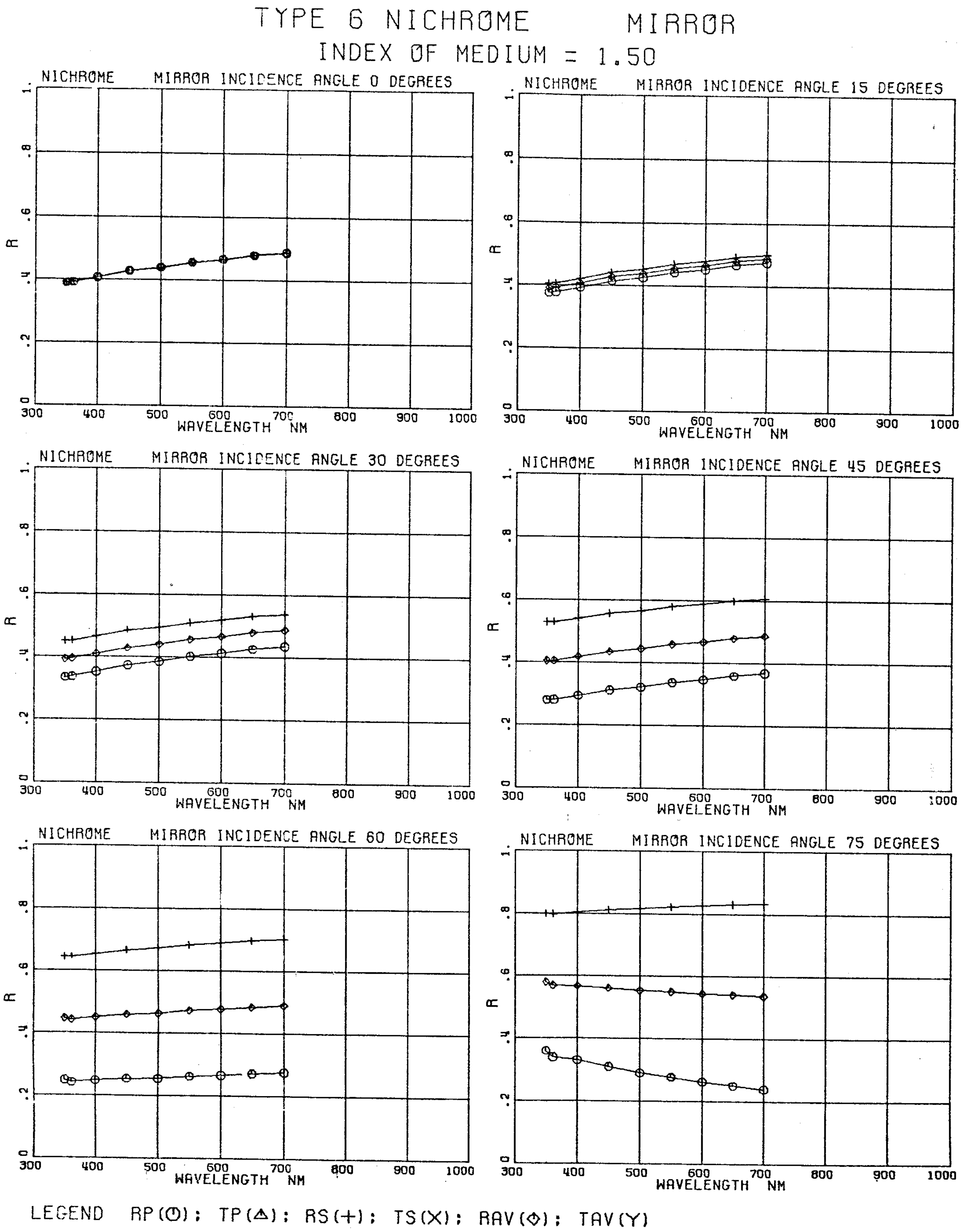


Figure 18. Nichrome mirror

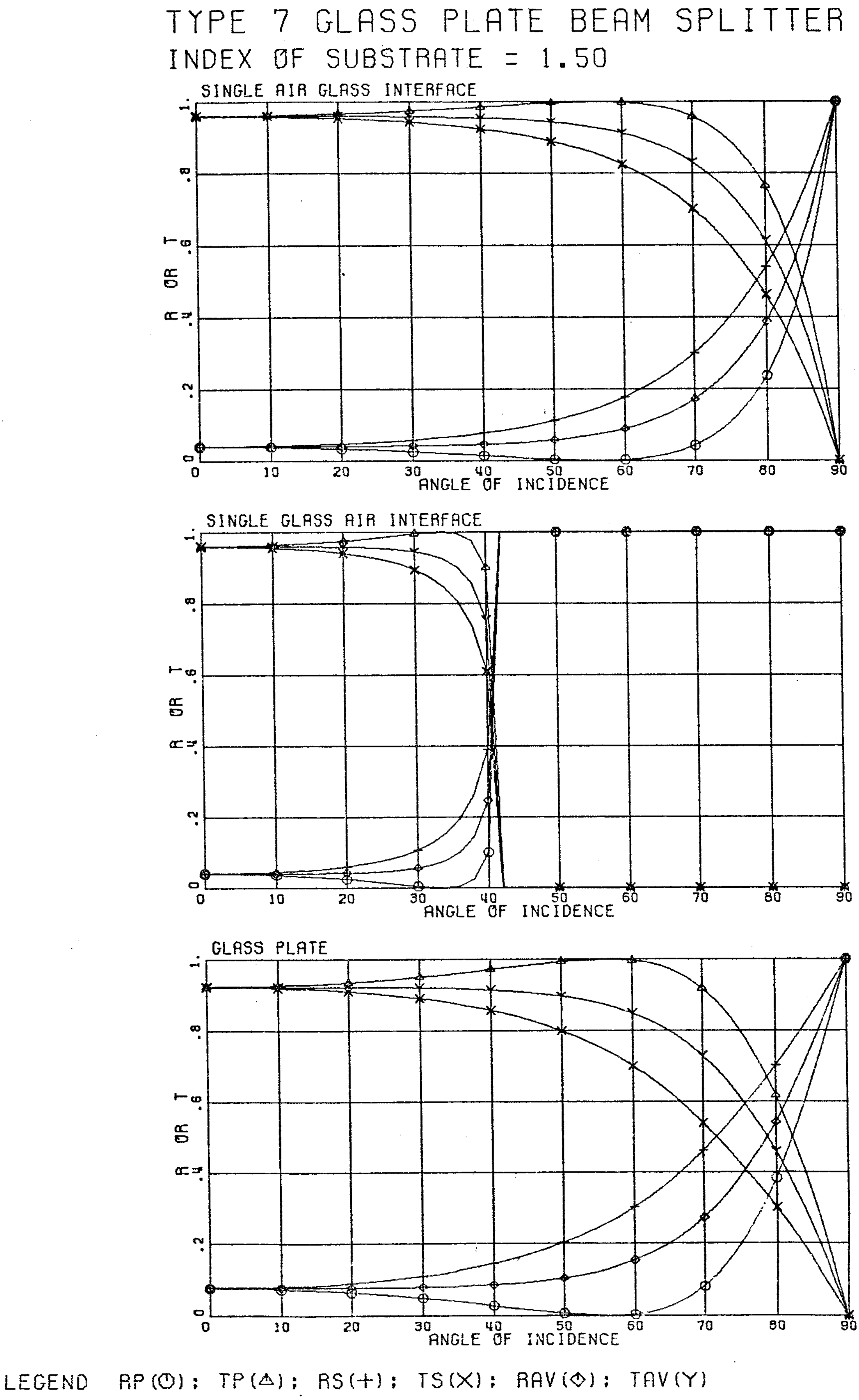


Figure 19. Glass plate beam splitter

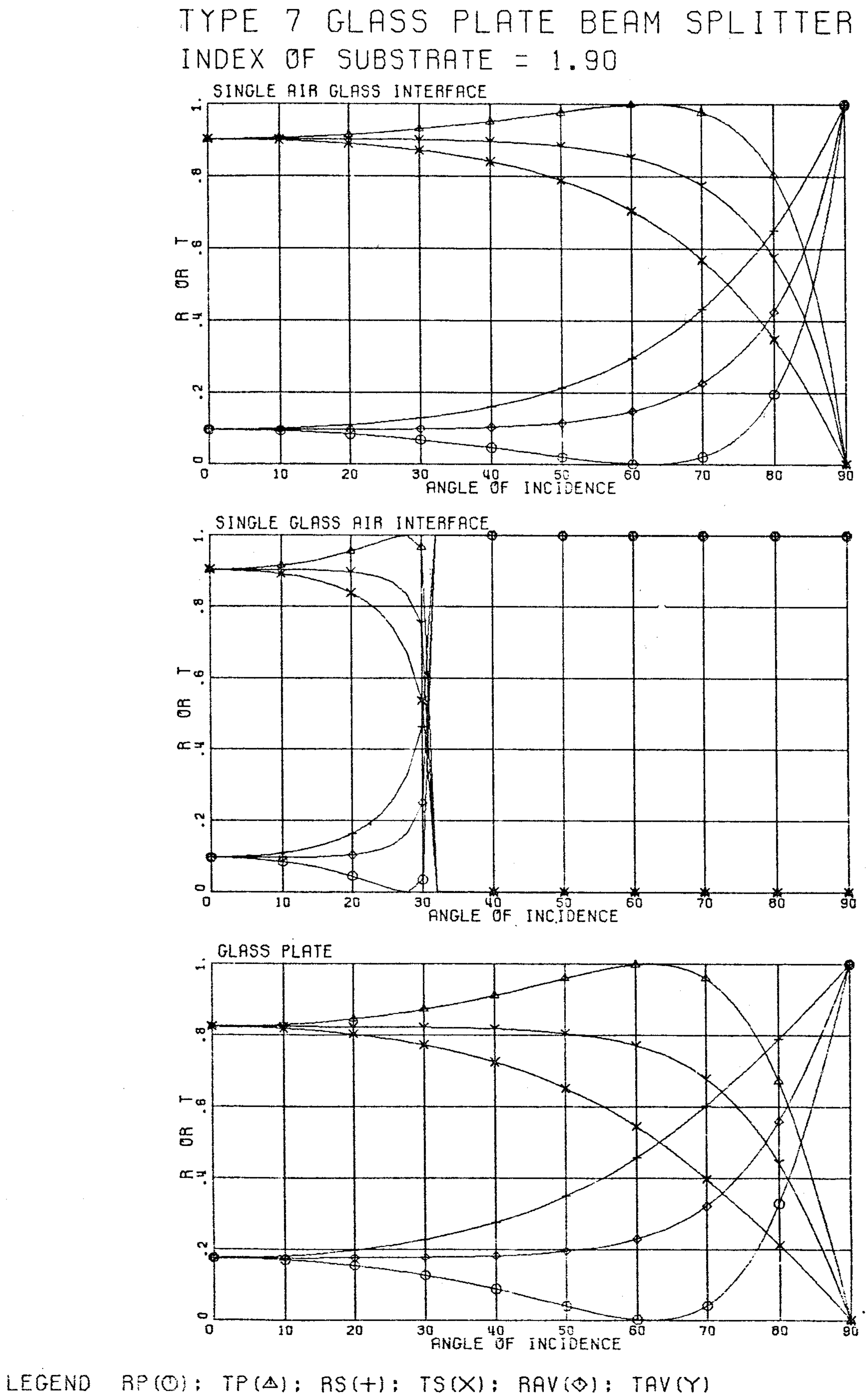
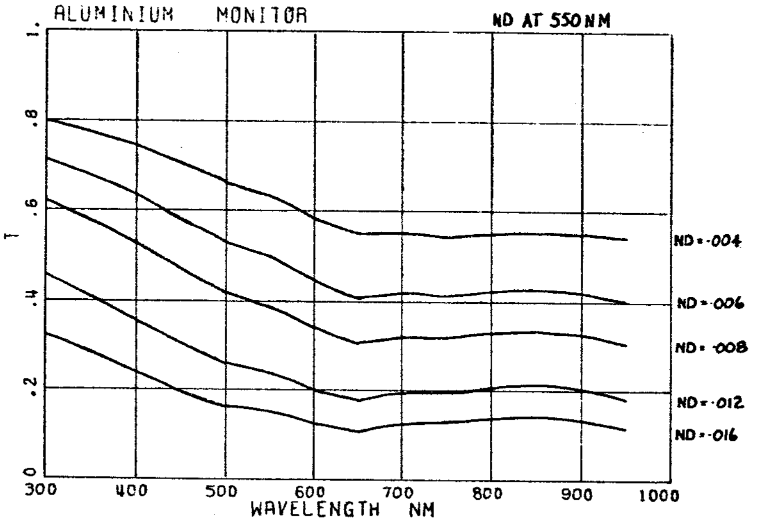


Figure 20. Glass plate beam splitter

TYPE 8 ALUMINIUM MONITOR
NORMAL INCIDENCE INDEX OF SUBSTRATE = 1.50



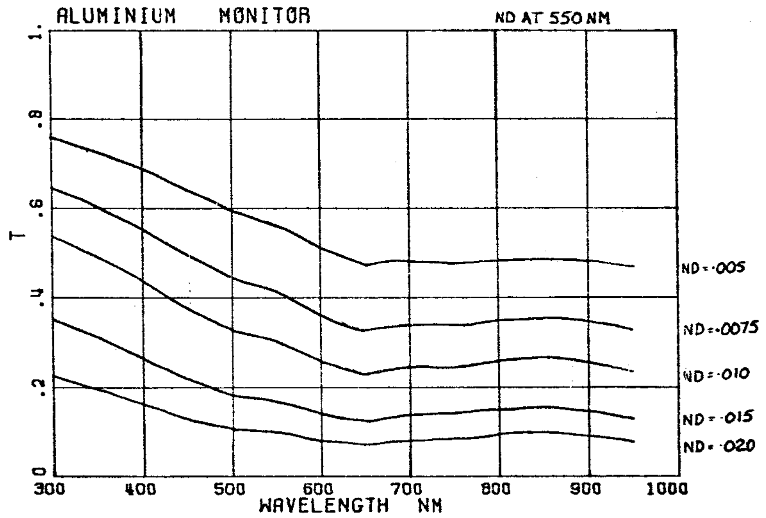


Figure 21. Aluminium monitors

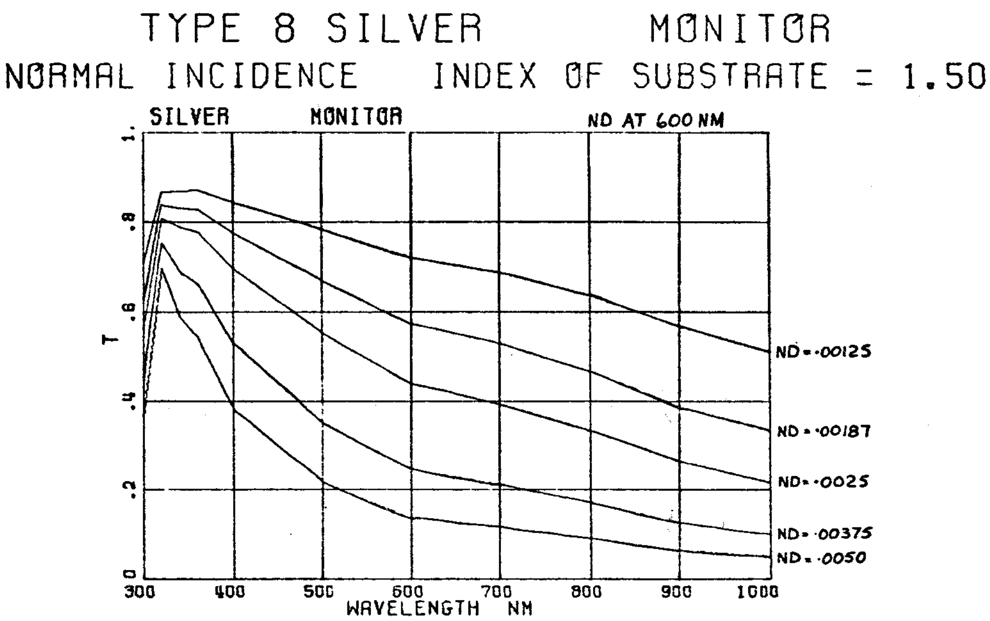


Figure 22. Silver monitors

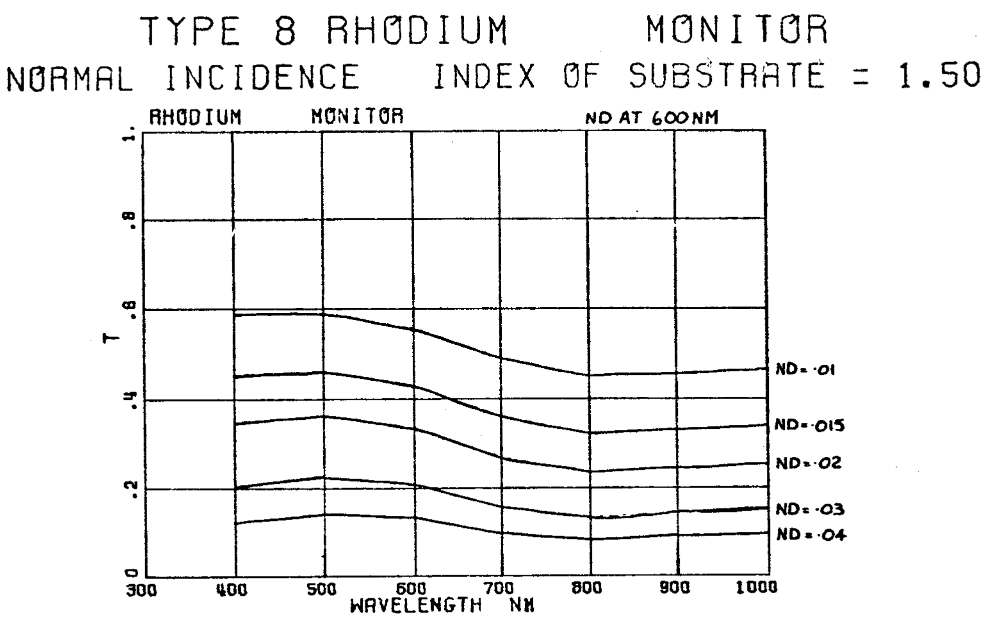
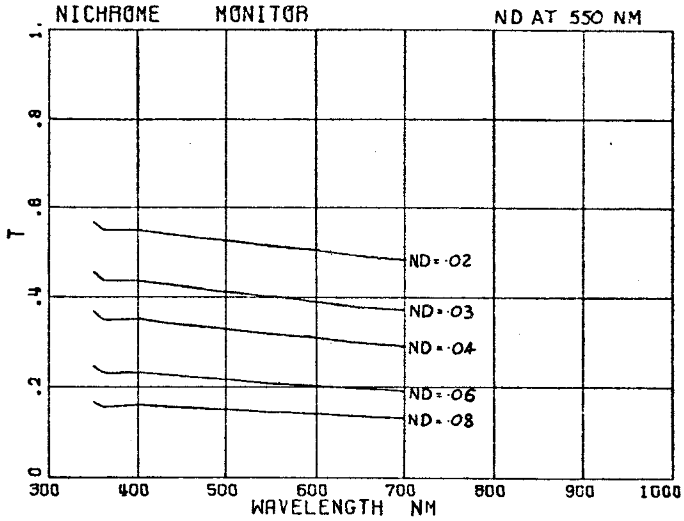
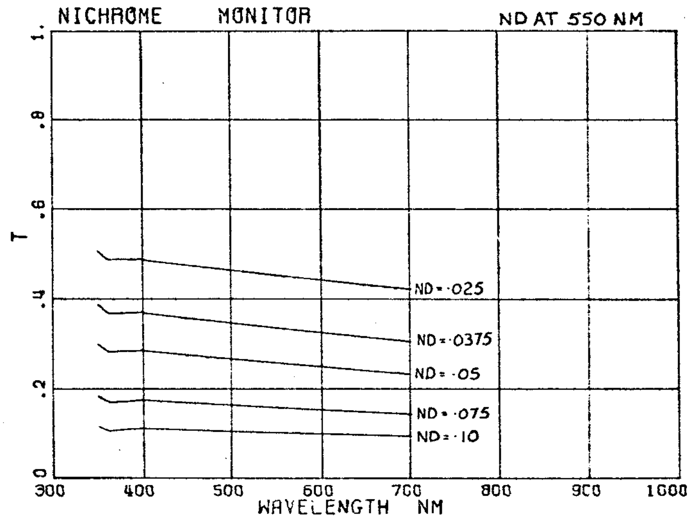


Figure 23. Rhodium monitors

TYPE 8 NICHROME MONITOR
NORMAL INCIDENCE INDEX OF SUBSTRATE = 1.50





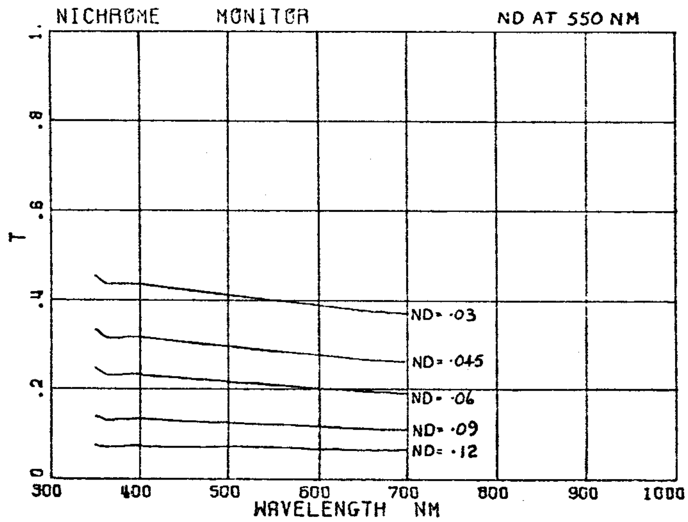


Figure 24. Nichrome monitors

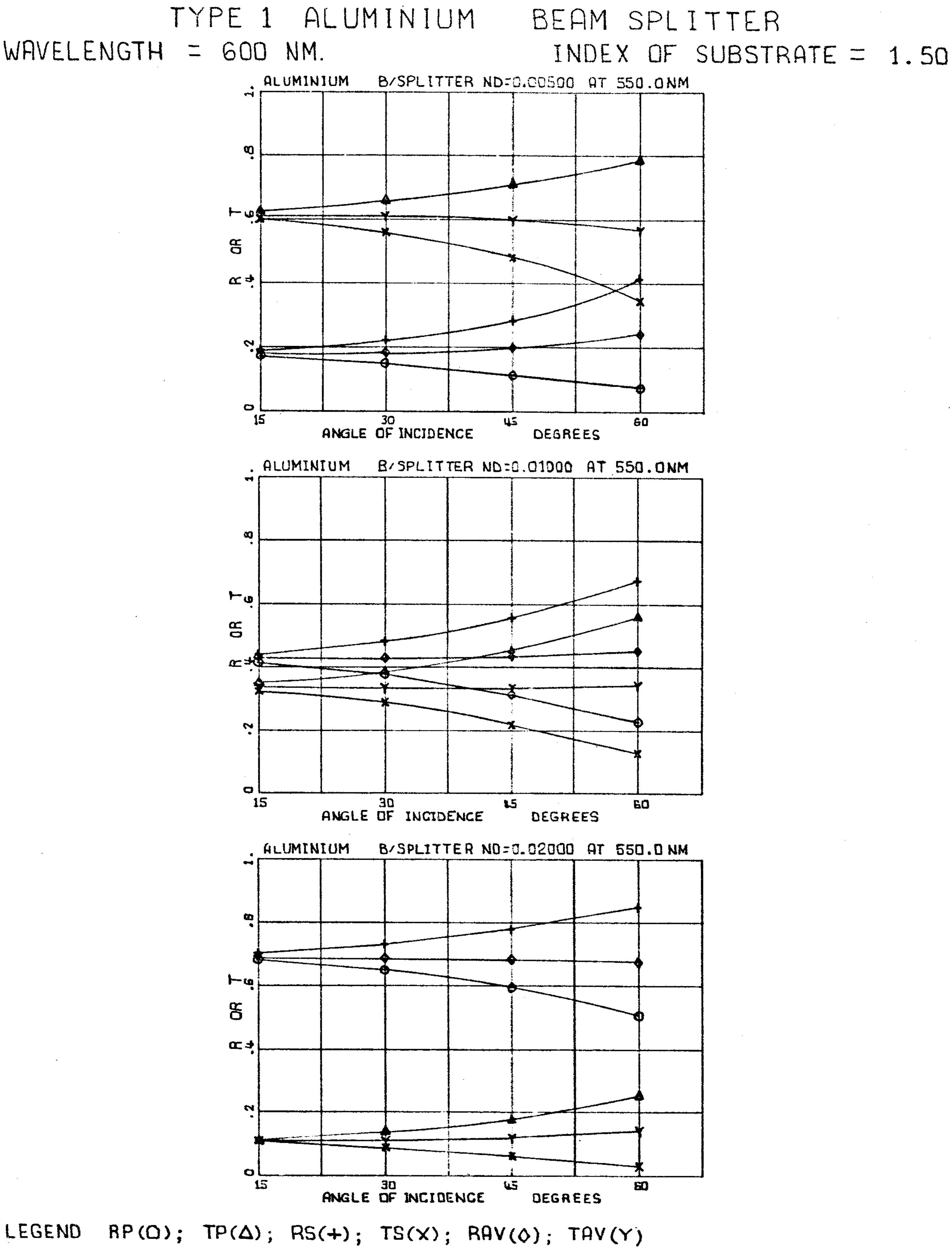
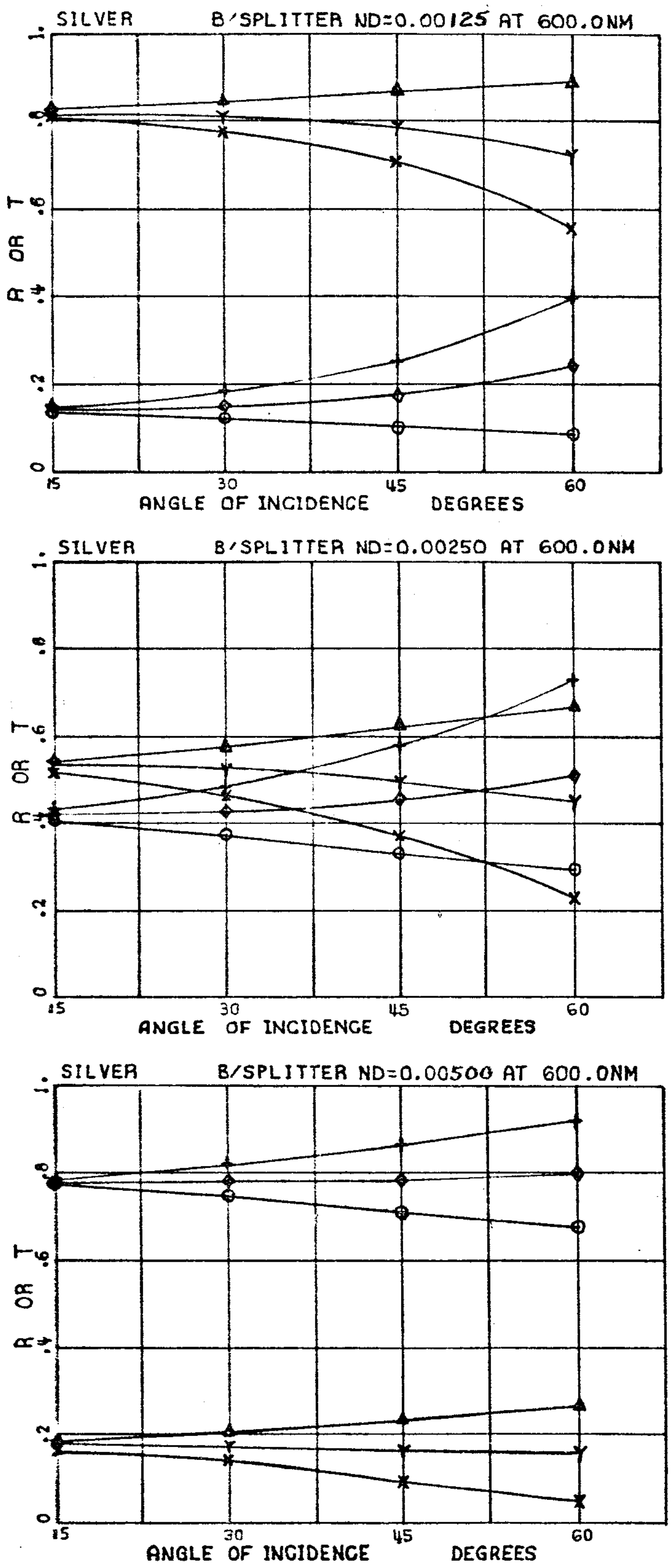


Figure 25. Variation of reflection and transmission characteristics of aluminium films as a function of angle of incidence and film thickness

TYPE 1 SILVER BEAM SPLITTER

WAVELENGTH = 600 NM. INDEX OF SUBSTRATE = 1.50



LEGEND RP(O); TP(△); RS(+); TS(X); RAV(◇); TAV(Y)

Figure 26. Variation of reflection and transmission characteristics of silver films as a function of angle of incidence and film thickness

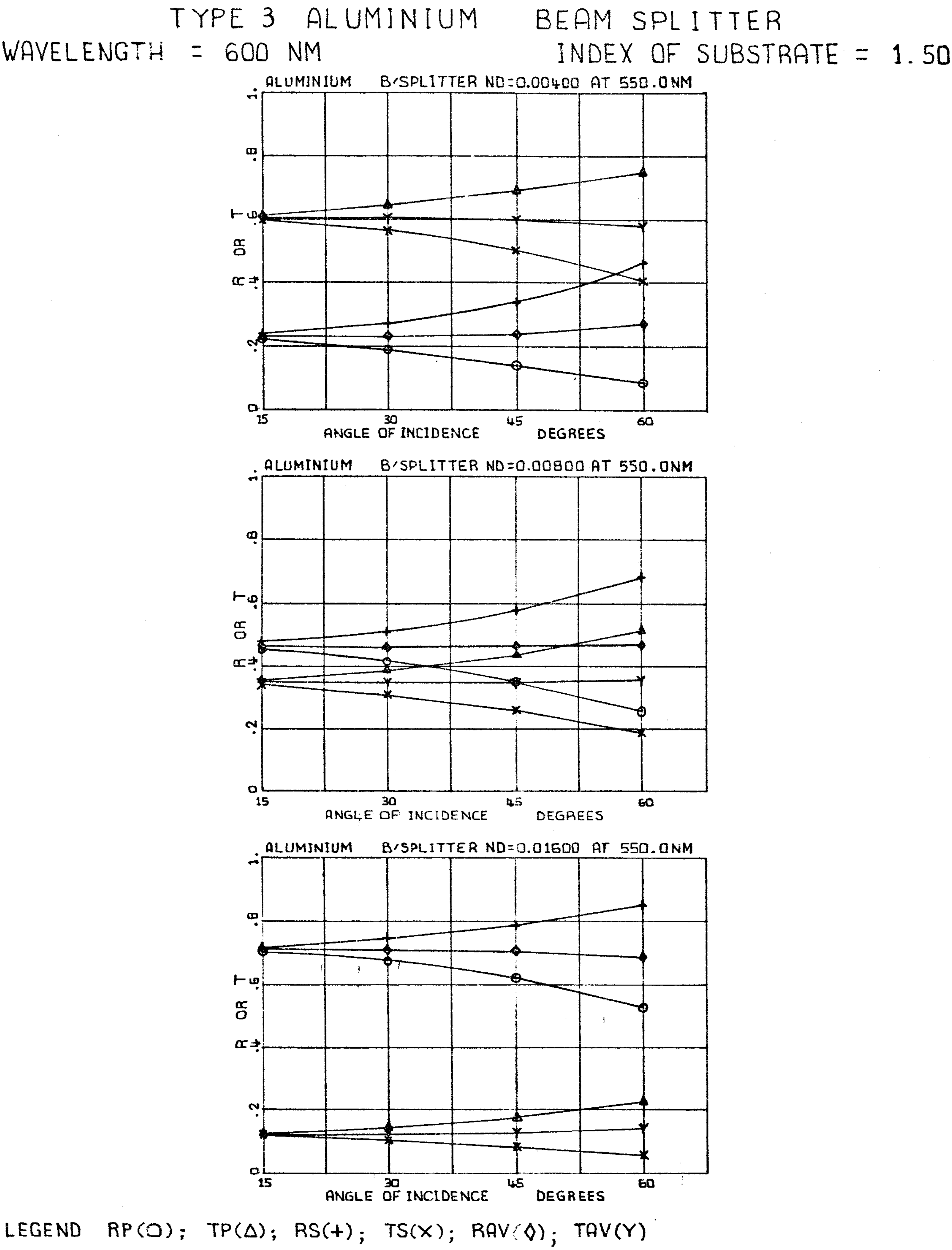


Figure 27. Variation of reflection and transmission characteristics of aluminium films as a function of angle of incidence and film thickness

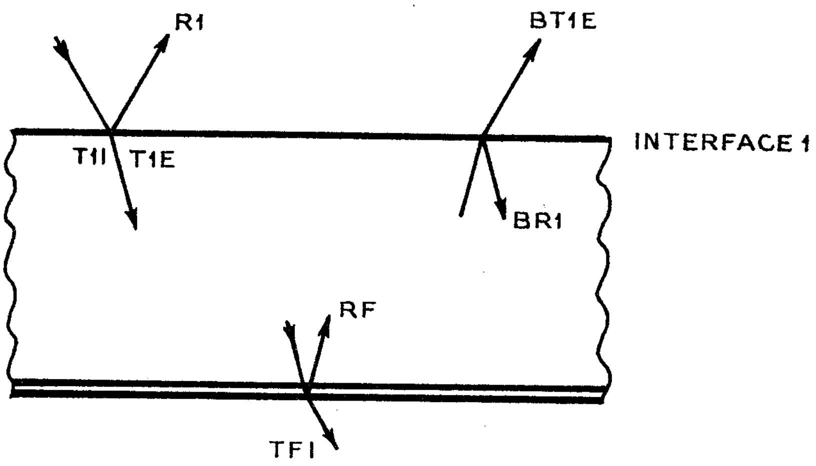


Figure 28. Notation for type 4 beam splitter

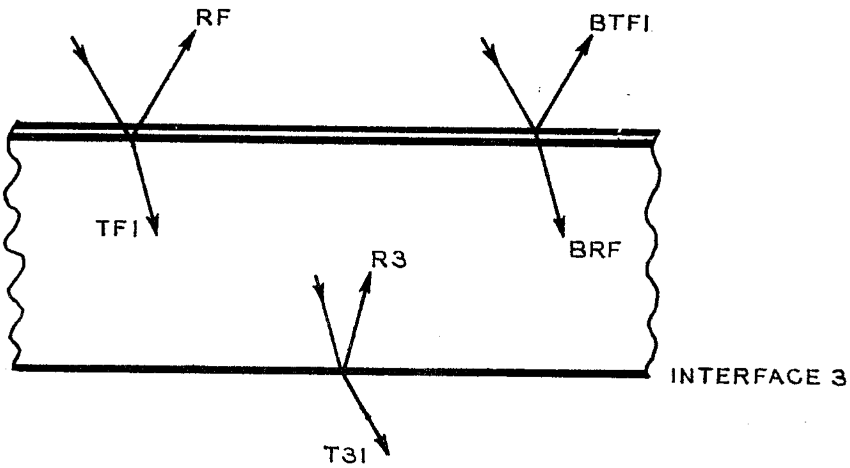


Figure 29. Notation for type 5 beam splitter

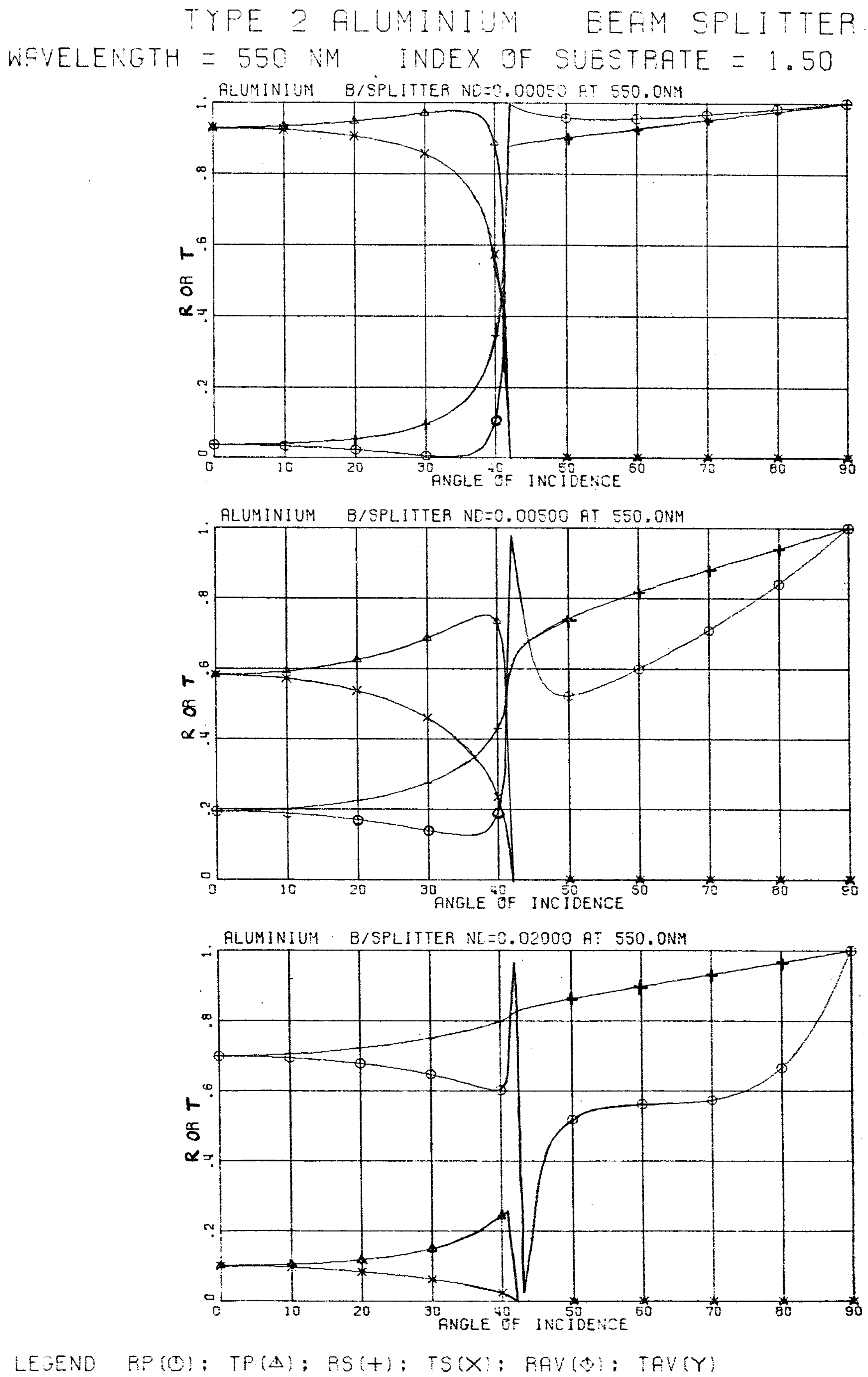
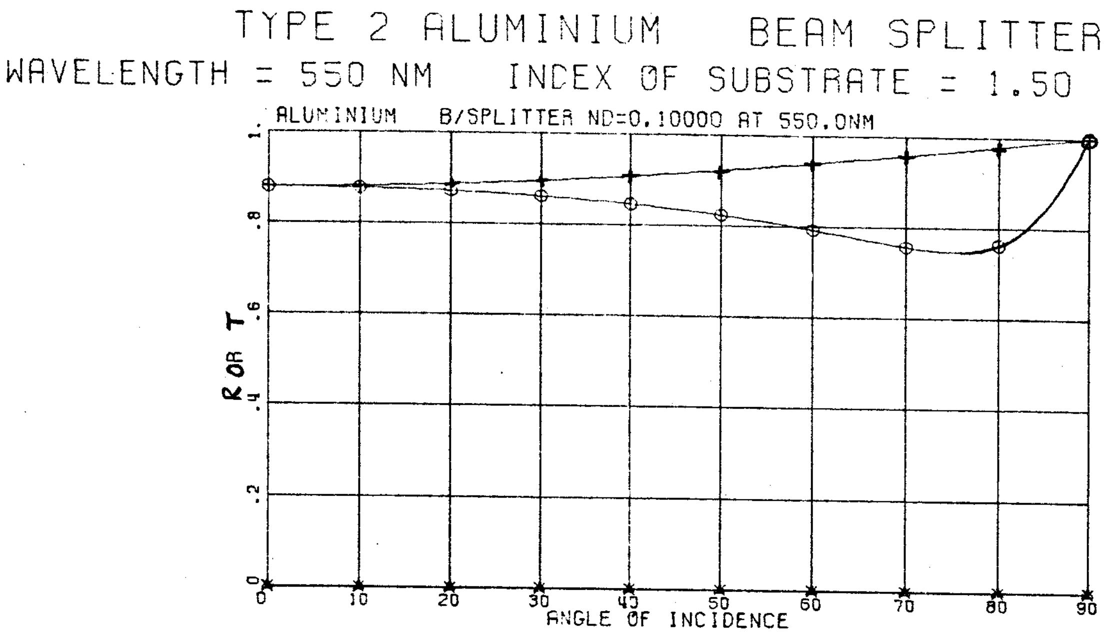


Figure 30. Variation of reflection and transmission coefficients at 550 nm wavelength of type 2 aluminium beam splitter as a function of angle of incidence and film thickness



LEGEND RP(O); TP(△); RS(+); TS(X); RAV(◇); TAV(Y)

Figure 30(Contd.). Variation of reflection and transmission coefficients at 550 nm wavelength of type 2 aluminium beam splitter as a function of angle of incidence and film thickness

DOCUMENT CONTROL DATA SHEET

Security classification of this page: UNCLASSIFIED

1 DOCUMENT NUMBERS	
AR Number:	AR-001-950
Report Number:	ERL-0123-TR
Other Numbers:	

2 SECURITY CLASSIFICATION	
a. Complete Document:	Unclassified
b. Title in Isolation:	Unclassified
c. Summary in Isolation:	Unclassified

3 TITLE

THE SPECTRAL CHARACTERISTICS OF METAL FILM BEAM SPLITTERS

4 PERSONAL AUTHOR(S):

J.R. Venning

5 DOCUMENT DATE:

JANUARY 1980

6

6.1 TOTAL NUMBER OF PAGES 49

6.2 NUMBER OF REFERENCES: 11

7

7.1 CORPORATE AUTHOR(S):

Electronics Research Laboratory

7.2 DOCUMENT SERIES AND NUMBER

Electronics Research Laboratory 0123-TR

8 REFERENCE NUMBERS

a. Task: DST 77/145

b. Sponsoring Agency:

9 COST CODE:

367021

10 IMPRINT (Publishing organisation)

Defence Research Centre Salisbury

11 COMPUTER PROGRAM(S) (Title(s) and language(s))

12 RELEASE LIMITATIONS (of the document):

Approved for Public Release

12.0	OVERSEAS	NO		P.R.	1	A		B		C		D		E	

Security classification of this page: UNCLASSIFIED

Security classification of this page: UNCLASSIFIED

13 ANNOUNCEMENT LIMITATIONS (of the information on these pages):

No limitation

14 DESCRIPTORS:

a. EJC Thesaurus Terms

	Metal coatings	Optical equipment
	Mirrors	Optical coatings
	Rhodium	Transmission
	Silver	Thin films
Beam splitters	Polarisation	Optical materials
Reflective coatings	Aluminium	Nichrome

b. Non-Thesaurus Terms

Optical constants
Beam splitters

15 COSATI CODES:

2006

16 LIBRARY LOCATION CODES (for libraries listed in the distribution):

17 SUMMARY OR ABSTRACT:
(if this is security classified, the announcement of this report will be similarly classified)

The spectral and polarisation characteristics of metallic beam splitters and mirrors made of single films of aluminium, silver, rhodium or nichrome on glass are described. Normal incidence transmission data of each thickness of metal film used in the beam splitter calculations is included for use when measuring or monitoring the deposition of the thin films. The presentation is mostly graphical and intended for the user and maker of simple metal beam splitters.

Security classification of this page: UNCLASSIFIED